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INFLUENCE OF VARIOUS FABRICATION METHODS ON THE COMPRESSIVE STRENGTH OF TITANIUM SKIN-STRINGER PANELS

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The quality of the joining methods was generally good as evidenced by the behavior of the skin-stringer panels in end compression. The joining methods maintained the integrity of the joint through buckling up to the maximum compressive strength of the panels. The maximum strengths of the panels showed good conformity with calculated results obtained from existing compressive strength analyses.

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SUMMARY

Thirty-seven skin-stringer panels were fabricated from Ti-8Al-1Mo-1V titanium alloy by riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) and electron-beam fusion welding, and diffusion bonding in order to investigate the effect of the various fabrication methods on the compressive strength. Also included in the investigation were two integrally stiffened panels machined from thick plate. The panels were representative of airplane wing or fuselage surfaces. Experimental buckling and maximum loads were determined for each panel. Results of strength tests for the various joining techniques were compared with each other and with compressive strength calculations.

The quality of the joining methods was generally good as evidenced by the behavior of the skin-stringer panels in end compression. The joining methods maintained the integrity of the joint through buckling up to the maximum compressive strength of the panels. The maximum strengths of the panels showed good conformity with calculated results obtained from existing compressive strength analyses.

Residual fabrication stress had a significant effect on compressive buckling and somewhat less effect on maximum strength. For panels with a stringer spacing equal to 30 times the skin thickness diffusion bonding and TIG fusion welding, stress relieved, ranked high (least effect of fabrication), and arc-spotwelding and machining ranked low (greatest effect of fabrication) for both buckling and maximum strength.

INTRODUCTION

Titanium alloys are being considered increasingly for application in structural components of both subsonic and supersonic aircraft. For a supersonic transport application, materials screening tests such as those described in references 1 and 2 have indicated that titanium alloys are prime candidates. The metallurgical characteristics of titanium alloys which favor joining by welding introduce the possibility of utilizing a number of different fabrication techniques. Titanium is more difficult to drill, machine, and cold-form than aluminum but is more amenable to high-strength welding and solid-state

diffusion bonding. However, few data have been available concerning the influence of various joining techniques on the load-carrying capabilities of fabricated components. Therefore, a program was initiated to investigate the compressive strength of structural components fabricated by a variety of techniques.

A skin-stringer panel was selected as a structural component representative of wing or fuselage surfaces. Essentially the same panel configuration was fabricated from titanium-alloy sheet by the use of riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) and electron-beam fusion welding, and diffusion bonding to join stringers to the skin. In addition, similar panels were machined from thick plate so that the stringers were integral with the skin.

After fabrication the panels were instrumented and then loaded to failure in end compression. Experimental buckling and maximum loads were determined for each panel. Results of strength tests for the various joining techniques were compared with each other and with compressive strength calculations.

SYMBOLS

The physical quantities in this paper are given both in U.S. Customary Units and in the International System of Units (SI). (See ref. 3.) Factors relating the two systems are given in appendix A.

A cross-sectional area of plate element, in^2 (m^2)

b width of plate element, in. (m)

b_A width of attachment flange of stringer (fig. 2), in. (m)

b_F width of outstanding flange of stringer (fig. 2), in. (m)

b_O geometric fastener offset, distance from center line of attachment to center line of stringer (fig. 2), in. (m)

b_S stringer spacing (fig. 2), in. (m)

b_W depth of web of stringer (fig. 2), in. (m)

C_F constant

E_s secant modulus, ksi (N/m^2)

n	number of plate elements
P	load, kips (N)
t	thickness of plate element, in. (m)
t_F	flange thickness (fig. 2), in. (m)
t_S	skin thickness (fig. 2), in. (m)
t_W	stringer thickness (fig. 2), in. (m)
σ	stress, ksi (N/m^2)
σ_f	plate element crippling stress, ksi (N/m^2)
$\bar{\sigma}_f$	panel crippling stress, ksi (N/m^2)

Subscripts:

max	maximum
cr	buckling
cy	compressive yield

TESTS

Materials and Test Specimens

The sheet and plate material used in the panel fabrication study was Ti-8Al-1Mo-1V titanium alloy supplied in three heat treated conditions: single or mill anneal (plate) and duplex and triplex anneal (sheet). The nominal thicknesses and the procedures for heat treating the material are given in table I.

Standard tensile and compressive specimens prescribed by the American Society for Testing and Materials (ASTM) were used for determining the mechanical properties of the sheet material. The specimens from the sheet material were machined with the long direction of the specimen parallel to the roll direction of the sheet. The specimens machined from the plate material were modified from the proposed standard in order to

use existing loading grips. Tensile and compressive specimens of circular cross section were machined from the plate material in the length, width, and thickness directions. (See fig. 1.)

The configuration of the skin-stringer panels is shown in figure 2. Sheet-metal panels were constructed with Z-, L-, and T-stringers and had the following nominal structural parameters: $\frac{b_S}{t_S} = 30$, $\frac{b_W}{t_W} = 30$, and $\frac{t_W}{t_S} = 0.8$ for duplex-annealed material $\left(\frac{t_W}{t_S} = 1.0 \text{ for triplex-annealed}\right)$. These panel proportions were selected so that local buckling would occur in the skin between stringers at a calculated stress of 75 ksi (520 MN/m^2), well below the nominal crippling stress of 85 ksi (590 MN/m^2). Thus the various types of joints would be bent and twisted by the buckling distortions to test their integrity up to the maximum compressive load. The stringers were joined to the face sheet by the following six methods: riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) and electron-beam fusion welding, and diffusion bonding. Panels machined from 1.75-inch-thick (44.5-mm) plate were designed with stringers of rectangular cross section and had the following nominal structural parameters: $\frac{b_S}{t_S} = 31$, $\frac{b_W}{t_W} = 14$, and $\frac{t_W}{t_S} = 1.7$. Table II gives the dimensions and mass of all the panels investigated. The design and fabrication procedures for constructing the panels are given in appendix B.

Test Procedures

Standard room-temperature stress-strain tests were made on each of the sheets used in the construction of the panels. The tensile specimens were tested in a hydraulic testing machine at a strain rate of 0.005 per minute through the 0.2-percent offset strain, and the strain rate was then increased to 0.05 per minute until fracture occurred. The compressive specimens, supported in a jig according to ASTM specifications, were tested in the same hydraulic machine at a strain rate of 0.005 per minute throughout the test. Tuckerman optical strain gages were used on both the tension and the compressive specimens to determine Young's modulus.

All the panels were tested at room temperature in end compression in the 1 200 000-pound-capacity (5.34-MN) universal static testing machine at the Langley Research Center. (See fig. 3.) Before testing, the ends of each panel were checked for parallelism and flatness to insure uniform loading through the panel.

Before testing, each panel was instrumented with resistance wire strain gages on the face sheet and stringers as shown in figure 4. Two arrangements of strain gages were used (for example, see figs. 4(a) and (d)), depending on anticipated panel response to loading. Data obtained from the strain gages were used to determine the occurrence

of buckling and to indicate the uniformity of loading in the panel skin and the stringer flanges. Deflectometers were used on both sides of the panels to determine shortening. Outputs from strain gages, deflectometers, and the load indicator were recorded at the Langley central digital data recording facility.

A load of 1 kip (4.4 kN) was used to preset the panels and check the recording system. The panels were then loaded to failure at a rate of approximately 10 kips per minute (0.7 kN/s). Data were recorded every 5 kips (22 kN) until approximately 50 percent of predicted maximum load was obtained. Data were then recorded at programed intervals of 3 seconds.

STRENGTH ANALYSIS

The basic panel configuration used throughout this investigation (fig. 2) was designed for local-crippling failure of the major elements – skin bays, stringer webs, and outstanding flanges. Riveted and welded connections were designed to be strong enough and sufficiently close-spaced to preclude tensile failures of the connections or buckling between rivets. However, as will be discussed later, two modes of failure were observed: local crippling for which the panels were designed and wrinkling which frequently occurs in panels when the stringers have attachment flanges. Therefore, each of these is considered in the following analysis of maximum compressive strength.

Local Crippling

Local crippling is a mode of failure in which the classical plate-buckling pattern that develops in individual elements of the panel continues to deepen as the load increases beyond the buckling load until a maximum load is reached. Figure 4(a) is a typical example of local crippling.

The compressive stress carried by a skin-stringer panel at maximum load for a local-crippling failure is calculated as the area-weighted average of the crippling stresses in the individual elements, as proposed in reference 4:

$$\bar{\sigma}_f = \frac{\sum_{i=1}^{n} \left(\sigma_f A\right)_i}{\sum_{i=1}^{n} A_i} \qquad (1)$$

where

$$\sigma_f = 1.60\left(E_s \sigma_{cy}\right)^{1/2}\left(\frac{t}{b}\right) \qquad (2)$$

for elements with both side edges supported, and

$$\sigma_f = C_F\left(E_s\sigma_{cy}^2\right)^{1/3}\left(\frac{t}{b}\right)^{2/3} \tag{3}$$

for flanges with one side edge supported and one side edge free. When two plate elements intersect at the supported edge, as in a Z-section, $C_F = 0.59$. When more than two plate elements intersect at the supported edge, as in a T-section, $C_F = 0.68$.

The secant modulus in equations (2) and (3) is evaluated from a compressive stress-strain curve at the stress value σ_f calculated from the appropriate equation. Thus a trial-and-error procedure is necessary if the crippling stress of an element is greater than the proportional limit. The compressive yield stress is taken as an upper limit for crippling stress in any element.

Wrinkling

Wrinkling of the skin occurs in compression panels when the stringers which stabilize the skin are attached by a flange in which the distance from the center line of the attachment to the center line of the stringer b_O exceeds a critical value. In this situation the flange behaves as a flexible cantilever spring and permits the attachment flange to deflect with the skin, thus forming a continuous wrinkle across the full width of the panel. (See figs. 4(b) and (c).) A thorough theoretical treatment of the wrinkling mode of panel buckling and failure is given in reference 5 for aluminum-alloy panels. Although the theory is completely general, it requires an input based on experimental data from panels fabricated with variations in rivet diameter, pitch, and offset from stringer center line. Reference 5 develops such an input based on numerous aluminum-alloy panel tests.

RESULTS AND DISCUSSION

Materials

The elastic modulus and compressive yield stress are the two material properties of greatest interest for compressive strengths of fabricated panels. Values of these compressive properties as well as the corresponding tensile properties are listed in table III for each thickness and heat treatment. The values are averages of four tests per sheet and from one to 14 sheets of material.

The data in table III indicate little difference between the compressive properties for the three different heat treatments. For specimens loaded in the longitudinal direction (the same loading direction as for the panels), properties of mill-annealed plate material were near the low end of the range of compressive yield stresses. For loading transversely in the plane of the plate the compressive yield stress was slightly greater, and

for loading in the thickness direction about 10 percent greater. Duplex-annealed sheet had an average compressive yield stress of 143 ksi (990 MN/m^2) with individual values ranging to ±7 percent. The only exception was the cap material in the diffusion-bonded T-stringer panels which had a compressive yield stress of 160 ksi (1100 MN/m^2) after exposure to the diffusion-bonding process (appendix B). Tensile tests of this same material indicated a possible embrittlement, as the elongation was only 2 percent. The properties of the diffusion-bonded web and skin material did not differ significantly from duplex-annealed properties. The triplex-annealed sheet had the highest strength with an average compressive yield stress of 147 ksi (1010 MN/m^2) and individual values ranging to ±2 percent.

Skin-Stringer Panels

Fabrication of 39 skin-stringer panels by seven different methods resulted in a variety of exterior skin surface conditions which are shown in the photographs of figure 4. TIG welding and electron-beam fusion welding left continuous seams on the panel surface; resistance-spotwelding left slight depressions in the surface of the panel, and arc-spotwelding left larger surface depressions. Two types of riveting were used: the triplex-annealed panels had countersunk monel rivets which, in some cases, were depressed below the skin surface; and the duplex-annealed panels had flat-head titanium-alloy rivets with a driven button protruding from the skin. Diffusion bonding of the sheet left the surfaces flat although there was some roughness due to sticking to the retort. Integrally stiffened panels machined from thick plate had smooth surfaces, but after machining, noticeable transverse curvature existed in the panel skin. Details of the fabrication processes are given in appendix B. With the exception of one of the diffusion-bonding processes, all fabrication methods produced good joints, which held the stringers to the skin throughout the deformations associated with panel compressive buckling and maximum strength.

Buckling.- All panels responded smoothly and uniformly to loading until the compressive buckling stress was reached. Experimental buckling stresses, given in table IV, were determined from two sources: the average stress at strain reversal when it occurred within the pattern of strain gages on the panel skin, and the average stress at deviation from initial linearity of the panel-shortening curves. In a few cases no buckling stress is reported because the buckle pattern developed in such a manner that none of the strain gages indicated a reversal and panel shortening did not show a significant point of deviation. The development of the buckle pattern with increasing load is illustrated in some of the photographic sequences of figure 4. Local buckling (fig. 4(a)) and wrinkling (figs. 4(b) and (c)) are quite evident in the panels fabricated from triplex-annealed material but are not as pronounced in similarly constructed panels of duplex-annealed material (figs. 4(d), (e), and (f)).

Considerable variation in buckling stresses was observed for the different types of fabrication (table IV) primarily because of residual fabrication stresses. For example, in the duplex-annealed material the TIG welded panels without stress relief carried an average buckling stress of 53 ksi (370 MN/m^2). This is substantially less than the buckling stress carried by any other type of fabrication as well as less than the calculated buckling stress of a simply supported plate (75 ksi (520 MN/m^2)). The panel of test 1 in table IV(b) was stress relieved after welding, and upon subsequent compressive loading, carried 73.4 ksi (506 MN/m^2) at buckling, an increase of approximately 40 percent.

The highest buckling stresses were obtained in panels fabricated by diffusion bonding Z-stringers. The lowest buckling stresses occurred in panels which were fabricated by TIG welding and arc-spotwelding.

Failure.- After buckling, all panels continued to carry increasing load until the maximum load was obtained (failure). Maximum compressive loads carried by the various panels are listed in table IV. A bar-graph comparison of panel strengths based on the average stress at maximum load is shown in figure 5. Experimental scatter is indicated by the two solid lines on each bar.

The diffusion-bonded panels have the greatest compressive strength, probably because of a lack of residual fabrication stress since they were bonded in a retort with the entire panel heated slowly and uniformly. Some of the improved strength is also due to the increased compressive modulus (table III(b)) which apparently results from the bonding heat cycle. However, it should be noted that although the panels that were bonded with an attachment flange failed in a wrinkling mode (fig. 4(g)) and were very consistent in failure strength (less than 4-percent spread), inadequate bonding caused premature failure of two of the five panels that were diffusion bonded with T-stringers and failed by crippling (fig. 4(h)), as indicated by dotted lines within the bar graph (fig. 5). Two similar panels had been rejected prior to loading on the basis of nondestructive test inspection. Thus, the T-type bonded joint requires additional quality control to insure satisfactory bonding along the entire length of each stringer.

The lowest compressive strengths occurred in the duplex-annealed panels that were fabricated by arc-spotwelding. These panels, which were quite consistent experimentally, carried about 25 percent less stress at failure than the strongest panels. At least two parameters influenced the experimental strength of these panels. Residual fabrication stresses were nearly as large as in the TIG panels, as indicated by the low buckling stresses. However, the effect of residual fabrication stresses was not alleviated by prior buckling to the same extent for wrinkling failures as it was for crippling failures. A similar effect on wrinkling failure was noted in reference 6 for residual thermal stresses, which had the same pattern as the residual fabrication stresses. The second

influence on the experimental strength was the arc-spotwelds themselves (fig. 4(i)), which were considerably larger in diameter and spaced farther apart than either the rivets or the resistance-spotwelds in other panels. Thus while the ratio of pitch to diameter was approximately maintained, there may have been an absolute size effect which influenced the experimental failures.

Panels fabricated by electron-beam welding had both Z- and L-type stringers. (See fig. 4(j).) Although both wrinkling and local-crippling failures developed corresponding to the two types of stringers, the joint strength was adequate. Approximately the same amount of residual fabrication stress should develop in both types of electron-beam welded panels since both incorporated continuous fusion welds.

In order to study more directly the influence of fabrication stress, two TIG welded panels, one duplex and one triplex, were stress relieved. A comparison of the panel strengths before and after stress relief is shown in figure 6. The 15-percent increase of failure strength due to stress relief is significant. Similar beneficial strength increases probably can be achieved by stress relief in most of the other forms of fabrication. The predicted values of panel compressive strength shown in figure 6 are based on calculations of local-crippling stress from equation (1). The agreement between these predicted values and the experimental strengths for stress-relieved panels indicates that residual fabrication stresses are the principal cause of the low strength of the as-fabricated panels.

A similar comparison between predicted values and the experimental compressive strengths for the other types of fabrication is shown in figure 7. Predictions based on two modes of failure are shown – local crippling and wrinkling. Local-crippling predictions were made from equation (1) for all the panel types. Wrinkling calculations can be made only for the panels with attachment flanges. It can be seen that the wrinkling predictions are as much as approximately 50 percent greater than the corresponding local-crippling predictions. Although six out of seven panels with attachment flanges failed experimentally in the wrinkling mode, the agreement with wrinkling predictions for these panels is very poor. The wrinkling theory of reference 5, which was developed for aluminum panels, would have to be modified considerably in order to bring it into agreement with experimental wrinkling failures of the titanium panels.

The rectangular stiffeners of the integrally stiffened panels machined from mill-annealed plate represent a considerable variation from the other stiffener configurations. (See fig. 4(k).) Failure of this type of panel was local crippling. The experimental compressive strength of these panels was quite low; however, predictions for local crippling are adequate, indicating that residual fabrication stresses due to machining were insignificant. The low strength can be directly related to the stringer configuration in this case.

With regard to the influence of fabrication method on compressive strength, the fabrication methods of duplex- and triplex-annealed materials show the same trend. In addition, the fabrication methods of duplex- and triplex-annealed materials show similar trends for the correlation of predicted and experimental strengths.

Ranking the various types of panels on the basis of the influence of the fabrication method on their compressive strength is complicated by the effects of the several stringer configurations used. However, within the group of panels having Z-stringers, diffusion bonding ranked the highest and arc-spotwelding ranked the lowest for compressive failure strength.

CONCLUDING REMARKS

The results of an investigation of the influence of various fabrication methods on the load-carrying capabilities of titanium-alloy skin-stringer panels have shown that the quality of these joining methods was generally good as evidenced by the behavior of the skin-stringer panels in end compression. The joining methods, riveting, resistance- and arc-spotwelding, TIG and electron-beam fusion welding, diffusion bonding, and machining, maintained the integrity of the stringer-to-skin joint through buckling up to the maximum compressive strength of the panel. The only exception to this was two of the five diffusion-bonded panels with T-stringers that failed prematurely by separation of stringer and face sheet. The maximum strengths of the other panels could be adequately predicted for the panels that failed by local crippling. For the panels that failed by wrinkling, the wrinkling predictions were as much as 50 percent high; however, a reasonable magnitude of failure stress was predicted by local crippling.

Neither crippling nor wrinkling failure predictions considered residual fabrication stresses, which apparently had the greatest effect on buckling of TIG welded panels. These residual stresses appeared to be alleviated when the panels were stress relieved, as evidenced by a significant improvement in buckling stress (40 percent) and somewhat less increase in maximum strength (15 percent). On the basis of compressive strength, panels with stringers joined to the skin by diffusion bonding and TIG welding, stress relieved, ranked high (least effect of fabrication), and those joined by arc-spotwelding and machining ranked low (greatest effect of fabrication) for both buckling and maximum strength.

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APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

Factors required for converting the U.S. Customary Units used herein to the International System of Units (SI) (ref. 3) are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit (**)
Area	in^2	6.4516×10^{-4}	meters^2 (m^2)
Force	kip	4.44822×10^3	newtons (N)
Length	in.	0.0254	meters (m)
Load rate	kips/min	0.07413	newtons/second (N/s)
Mass	lbm	0.4536	kilograms (kg)
Pressure	psi	6.895×10^3	newtons/meter^2 (N/m^2)
	torr	1.333×10^2	newtons/meter^2 (N/m^2)
Speed	in./min	4.233×10^3	meters/second (m/s)
Stress	ksi	6.895×10^6	newtons/meter^2 (N/m^2)
Temperature . . .	^oF	$\frac{5}{9}(F + 459.67)$	degrees Kelvin (^oK)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

**Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}

APPENDIX B

DETAILS OF THE DESIGN AND FABRICATION OF SKIN-STRINGER PANELS

Panel Design

The skin-stringer panels shown in figure 2 were designed for compressive loading and local-crippling failure. Six stringers were to be attached to the skin by various fabrication methods: riveting, resistance-spotwelding, arc-spotwelding, TIG fusion welding, electron-beam fusion welding, and diffusion bonding. (However, the electron-beam welded panels had only five stringers. A discussion of this reduction is given in the section on electron-beam welding.) Panel proportions were selected so that local buckling would occur in the skin between stringers and in the webs and flanges of the stringers at a nominal stress of 75 ksi (520 MN/m^2), well below the nominal crippling failure stress of 85 ksi (590 MN/m^2). Thus the various types of joints (fig. 2) would be bent and twisted by the buckling distortions to test their integrity up to the maximum compressive load that could be sustained by the panel.

To satisfy the above buckling requirement, the panels were designed to a nominal $\frac{b}{t} = 30$ for the skin and the webs of the stringers. A stringer thickness eight-tenths of the skin thickness was selected so that the various joining methods would have to be applied to two unequal thicknesses of material. The initial set of panels was designed to be quickly fabricated from triplex-annealed material that was already on hand. However, only one sheet thickness was available, and therefore the skin and stringers of these initial panels were of the same thickness. Panel length was designed to be seven times the stringer spacing for all panels so that six or seven local buckles could form in each of the skin bays between stringers. This length was about one-third the length that would be required in order to have failures occur by column buckling instead of local crippling.

The Z-stringers were brake-formed from sheet material to the minimum bend radius that could be achieved in a warm brake. The width of the outstanding flange was designed to be four-tenths of the stringer web width, a ratio that has been used extensively for aluminum-alloy panels. (See ref. 7, for example.) The width of the attachment flange was the minimum required for adequate clearance of the various joining tools from the stringer webs and for maintaining an edge distance of 1.5 diameters. Panels for two types of joining, diffusion bonding and electron-beam welding, were designed both with and without attachment flanges (fig. 2); TIG welded joints, designed to be fabricated without attachment flanges, were welded through the skin directly into the edge of the web. Fabrication details for all the methods of joining are given in the succeeding section.

A variation of the fabricated sheet-metal panel was machined from plate stock 1.75 inches (4.45 cm) thick and 12 inches (30 cm) wide. The panel was designed with

stringers of rectangular cross section and was proportioned to the same nominal failure stress as the sheet-metal panels; however, the actual skin thickness was slightly greater.

Fabrication

The Ti-8Al-1Mo-1V titanium-alloy skin-stringer panels were fabricated by seven different construction methods. Six of the seven methods involved sheet-metal joining procedures, some standard and some rather specialized, and the seventh method considered was machining the panel as an integral unit from thick plate. All sheet-metal components for panel construction were sheared from the as-received sheet and hand deburred by filing lightly over the edges. The L-stringers for the TIG and electron-beam welded panels were machined across the attachment edge to obtain good metal-to-metal contact between the stringer and skin. The Ti-8Al-1Mo-1V duplex-annealed material for the Z- and L-stringers was preheated in an oven to 250° or 300° F (390° or 420° K) and was then formed over a preheated die of 3/16-inch (0.48-cm) radius. The stringers made from Ti-8Al-1Mo-1V triplex-annealed material were brake-formed at room temperature. After the stringers were formed, the panels were constructed by the methods described in the following sections.

Tungsten inert-gas welding.- The tungsten inert-gas (TIG) welding was accomplished with an automatic welding head. The TIG welded panels were constructed with L-stringers. To insure a good weld with no depression on the external side, the skin was channeled with grooves 0.050 inch (1.27 mm) wide by 0.010 inch (0.25 mm) deep in which the stringers were "seated" before welding. The panel was set up for welding in such a way that the area being welded was completely purged with argon. This was accomplished by placing the stringer to be welded between two square copper tubes. The edge of the tube nearest the weld was mitered, and small holes were drilled along its length. Argon was pumped through the copper tubing and allowed to escape through the holes to protect the joint during TIG welding. The weld was also protected on the external side by blowing helium over the weld. Helium was used rather than argon because a hotter arc, resulting in better penetration, is achieved in helium. The bead formed by welding was slightly convex and protruded from the plane of the skin. This bead was removed by an end mill, leaving a smooth surface with no indentations or irregularities.

Several panels were TIG welded by utilizing Ti-8Al-1Mo-1V titanium-alloy filler wire instead of channeling the skin. There were no apparent differences in maximum strengths or failures due to the differences in welding procedures. Both the duplex- and triplex-annealed panels were welded by the same procedures with only slight modifications in the parameters.

Riveting.- The riveted panels were constructed by standard shop procedures. The holes for the rivets were drilled in the skin and stringers with cobalt drills.

Ti-8Al-1Mo-1V titanium-alloy rivets 1/8 inch (3.2 mm) in diameter machined from round bar stock were used to fasten the duplex-annealed panels, and 1/8-inch-diameter (3.2-mm) monel rivets were used to fasten the triplex-annealed panels. The rivets were squeeze-headed without preheat treatment.

Resistance-spotwelding.- The resistance-spotwelds were made by standard shop procedures. Good quality welds were obtained, and the size and penetration are given in the following table:

	Duplex-annealed sheet	Triplex-annealed sheet
Skin thickness	0.064 in. (1.63 mm)	0.050 in. (1.27 mm)
Stringer thickness	0.050 in. (1.27 mm)	0.050 in. (1.27 mm)
Weld diameter	0.14 in. (3.5 mm)	0.19 in. (4.8 mm)
Penetration	60 percent	75 percent

Arc-spotwelding.- Arc-spotwelding was accomplished on a heliarc-spotwelder with argon for the shielding gas. The panels (0.064-inch (1.63-mm) skin thickness) were constructed with only Z-stringers (0.050-inch (1.27-mm) thickness). The stringers were tack-welded to the panel before arc-spotwelding. To control the puddle diameter of the weld a heat sink was developed by using copper washers 1/8 inch (3.18 mm) thick and 1 inch (25 mm) in diameter. By using the washer, the puddle size is kept approximately the same size as the inside diameter of the washer (3/8 inch (9.5 mm)). The preweld purge time was 360 cycles at 60 hertz. This weld was made with an electrode diameter of 1/8 inch (3.18 mm), a constant voltage of 15, a weld time of 105 cycles at 60 hertz, and an arc length of 0.045 inch (1.14 mm). A second weld was made on top of the first weld to fill in the deep pit made by the first. The second weld was also made at 15 volts but for only 30 cycles at 60 hertz. The second weld also increased the weld-area nugget diameter without increasing the diameter of the weld puddle. The postweld purge time was 360 cycles at 60 hertz.

Electron-beam welding.- Both Z- and L-stringers were used on the panels fabricated by electron-beam welding. For the Z-stringer panels, two parallel weld lines were made to fasten each stringer attachment flange to the skin. Only one weld was made to bond the L-stringer to the skin. Because of the vacuum-chamber size, these panels had to be reduced in both length and width (table II(b)). The panels had four bays (five stringers), and the length was slightly over $5b_S$. The following table gives the welding parameters used to fabricate the panels:

	L-stringer	Z-stringer
Table speed	20 in./min (8.5 mm/s)	20 in./min (8.5 mm/s)
Deflection	0.050 inch (1.3 mm) (across weld)	0.030 inch (0.8 mm) (direction of weld)
Weld width	0.070 inch (1.8 mm)	0.062 inch (1.6 mm)
Weld penetration	0.090 inch (2.3 mm)	0.112 inch (2.8 mm)
Vacuum	10^{-5} torr (1 mN/m^2)	10^{-5} torr (1 mN/m^2)

Diffusion bonding.- The diffusion-bonding process utilized in fabricating Z-stringer panels resulted from an investigation to determine optimum bonding parameters. Concurrent with this investigation was another study to construct a retort in which the panels could be diffusion bonded. As a result of these two studies, the panels were bonded in a stainless-steel retort at a bonding temperature of 1800° F (1260° K) for 1 hour. The retort was evacuated to a pressure of 10^{-4} torr to 10^{-5} torr (10 to 1 mN/m^2) which prevented oxidation and produced a bonding pressure of 137 psi (0.94 MN/m^2). No "stop off" material or compound was used to prevent the titanium from bonding with the stainless-steel retort, but only a light tap was required to separate the panel from the retort.

The diffusion-bonding process utilized in fabricating T-stringer panels was different from that for the Z-stringer panels. The size of the bonding retort allowed four panels to be bonded simultaneously. After the components were sheared from the sheets, the webs and caps were ground to final width. Following the grinding, all components were deburred and cleaned, and all bonding surfaces were sanded until a bright smooth finish was obtained. All components were then etched for 1 minute in a solution of 30 percent HNO_3, 4 percent HF, and 66 percent H_2O, rinsed in de-ionized water for 5 minutes, and wiped dry with lint-free towels. All bonding surfaces were resanded, rinsed in distilled water, and wiped dry.

The components were placed in a lay-up fixture which properly located the parts and held them in position for heliarc-tack-welding at each end of the webs. The assembled components were placed in a stainless-steel envelope for bonding. In order to prevent crushing of the webs and to hold parts in their correct position during bonding, mild-steel support bars were coated with boron nitride and placed on each side of each web between the skin and cap. Bonding was done in a vacuum of 10^{-5} torr (1 mN/m^2). The panels were heated to 1800° F (1260° K) with short holds at 600° F (590° K), 900° F (760° K), 1400° F (1030° K), and 1600° F (1150° K) for outgassing. The panels were held for 4 hours at 1800° F (1260° K), and then the temperature was reduced to 1450° F (1060° K) and held there for 30 minutes. The temperature was then reduced to 900° F (760° K) in 5 minutes, and subsequently the panels were allowed to cool to room temperature.

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TABLE I.- DESCRIPTION OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET AND PLATE MATERIALS AND HEAT TREATMENTS

Condition	Nominal thickness		Heat treatment (a)
	in.	mm	
Mill-annealed plate	1.75	44.5	Annealed 8 hours at 1450° F (1060° K) and furnace cooled
Duplex-annealed sheet	.050 .064	1.27 1.63	Mill-annealed plus 15 minutes at 1450° F (1060° K) with an air cool
Triplex-annealed sheet	.050	1.27	Mill-annealed plus 5 minutes at 1850° F (1280° K) with an air cool plus 15 minutes at 1375° F (1020° K) with an air cool

[a]Vendor supplied information.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS

(a) Integral panels machined from mill-annealed plate

U.S. Customary Units								
Test	Mass, lbm	Length, in.	Width, in.	Area,[a] in^2	b_S, in.	b_W, in.	t_S, in.	t_W, in.
1	3.162	10.93	12.02	1.830	2.18	1.61	0.073	0.096
2	3.517	10.95	12.00	2.030	2.17	1.61	.071	.117

SI Units								
Test	Mass, kg	Length, mm	Width, mm	Area,[a] cm^2	b_S, mm	b_W, mm	t_S, mm	t_W, mm
1	1.43	278	305	11.8	55.4	40.9	1.9	2.4
2	1.60	278	305	13.1	55.1	40.9	1.8	3.0

[a]Cross-sectional area of stiffened panel.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Continued

(b) Panels fabricated from duplex-annealed sheet

U.S. Customary Units														
Test	Panel type	Mass, lbm	Length, in.	Width, in.	Area,[a] in^2	b_S, in.	b_W, in.	b_F, in.	b_A, in.	b_O, in.	t_S, in.	t_W, in.	t_F, in.
1	Tungsten inert-gas welded	2.587	13.28	10.49	1.233	1.95	1.34	0.53	---	---	0.063	0.052	0.052
2		2.603	13.33	10.46	1.236	1.94	1.31	.52	---	---	.064	.053	.053
3		2.616	13.35	10.45	1.240	1.94	1.33	.53	---	---	.063	.052	.052
4	Riveted	2.890	13.68	10.20	1.339	1.95	1.34	0.55	0.43	0.24	0.067	0.051	0.051
5		2.956	13.69	10.21	1.367	1.95	1.35	.55	.43	.25	.067	.052	.052
6		2.896	13.65	10.20	1.343	1.95	1.33	.56	.43	.18	.067	.050	.050
7	Resistance-spotwelded	3.010	13.67	10.30	1.394	1.95	1.36	0.54	0.55	0.33	0.065	0.052	0.052
8		3.021	13.68	10.29	1.396	1.95	1.36	.54	.55	.32	.065	.053	.053
9		3.025	13.66	10.32	1.400	1.95	1.36	.55	.55	.33	.066	.052	.052
10	Arc-spotwelded	2.999	13.65	10.56	1.394	1.95	1.36	0.55	0.56	0.39	0.068	0.050	0.050
11		3.006	13.22	10.57	1.439	1.96	1.36	.56	.56	.38	.068	.050	.050
12		3.020	13.71	10.57	1.391	1.96	1.35	.54	.54	.35	.069	.051	.051
13	Electron-beam welded (Z)	1.774	10.05	8.56	1.117	1.94	1.34	0.54	0.43	0.25	0.067	0.050	0.050
14		1.790	10.05	8.58	1.127	1.95	1.33	.52	.42	.27	.067	.051	.051
15		1.787	10.04	8.58	1.127	1.95	1.36	.53	.44	.28	.067	.050	.050
16	Electron-beam welded (L)	1.601	10.04	8.24	1.009	1.95	1.39	0.53	---	---	0.066	0.050	0.050
17		1.612	10.03	8.25	1.017	1.96	1.37	.52	---	---	.067	.051	.051
18		1.610	10.04	8.25	1.015	1.96	1.35	.52	---	---	.067	.051	.051
19	Diffusion bonded (Z)	2.817	13.28	10.31	1.340	1.95	1.41	0.56	0.55	0.24	0.066	0.048	0.048
20		2.878	13.65	10.32	1.335	1.95	1.40	.55	.55	.30	.065	.049	.049
21		2.383	13.71	8.40	1.100	1.95	1.39	.55	.56	.32	.065	.049	.049
22		2.899	13.70	10.33	1.340	1.95	1.38	.56	.56	.30	.065	.049	.049
23	Diffusion bonded (T)	2.602	13.52	10.28	1.215	1.95	1.28	0.29	---	---	0.067	0.048	0.049
24		2.584	13.43	10.22	1.215	1.94	1.29	.29	---	---	.067	.048	.050
25		2.568	13.62	10.24	1.195	1.95	1.28	.29	---	---	.066	.049	.051
26		2.628	13.58	10.24	1.230	1.95	1.28	.29	---	---	.067	.049	.050
27		2.485	13.60	10.24	1.158	1.95	1.28	.29	---	---	.062	.048	.049

[a]Cross-sectional area of stiffened panel.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Continued

(b) Panels fabricated from duplex-annealed sheet – Concluded

SI Units													
Test	Panel type	Mass, kg	Length, mm	Width, mm	Area,[a] cm^2	b_S, mm	b_W, mm	b_F, mm	b_A, mm	b_O, mm	t_S, mm	t_W, mm	t_F, mm
1	Tungsten	1.17	337	266	7.95	49.5	34.0	13.5	---	---	1.6	1.3	1.3
2	inert-gas	1.18	339	266	7.97	49.2	33.3	13.2	---	---	1.6	1.3	1.3
3	welded	1.19	339	265	8.00	49.2	33.8	13.5	---	---	1.6	1.3	1.3
4		1.31	347	259	8.64	49.5	34.0	14.0	10.9	6.1	1.7	1.3	1.3
5	Riveted	1.34	348	259	8.82	49.5	34.3	14.0	10.9	6.4	1.7	1.3	1.3
6		1.31	347	259	8.66	49.5	33.8	14.2	10.9	4.6	1.7	1.3	1.3
7	Resistance-	1.37	347	262	8.99	49.5	34.5	13.7	14.0	8.4	1.7	1.3	1.3
8	spotwelded	1.37	347	261	9.01	49.5	34.5	13.7	14.0	8.1	1.7	1.3	1.3
9		1.37	347	262	9.03	49.5	34.5	14.0	14.0	8.4	1.7	1.3	1.3
10	Arc-	1.36	347	268	8.99	49.5	34.5	14.0	14.2	9.9	1.7	1.3	1.3
11	spotwelded	1.36	335	268	9.28	49.8	34.5	14.2	14.2	9.7	1.7	1.3	1.3
12		1.37	348	268	8.97	49.8	34.3	13.7	13.7	8.9	1.8	1.3	1.3
13	Electron-	0.81	255	217	7.21	49.2	34.0	13.7	10.9	6.4	1.7	1.3	1.3
14	beam	.81	255	218	7.27	49.5	33.8	13.2	10.7	6.9	1.7	1.3	1.3
15	welded (Z)	.81	255	218	7.27	49.5	34.5	13.5	11.2	7.1	1.7	1.3	1.3
16	Electron-	0.73	255	209	6.51	49.5	35.3	13.5	---	---	1.7	1.3	1.3
17	beam	.73	255	210	6.56	49.8	34.8	13.2	---	---	1.7	1.3	1.3
18	welded (L)	.73	255	210	6.55	49.8	34.3	13.2	---	---	1.7	1.3	1.3
19		1.28	337	262	8.65	49.5	35.8	14.2	14.0	6.1	1.7	1.2	1.2
20	Diffusion	1.31	347	262	8.61	49.5	35.6	14.0	14.0	7.6	1.7	1.2	1.2
21	bonded (Z)	1.08	348	213	7.10	49.5	35.3	14.0	14.2	8.1	1.7	1.2	1.2
22		1.31	348	262	8.65	49.5	35.0	14.2	14.2	7.6	1.7	1.2	1.2
23		1.18	343	261	7.84	49.5	32.5	7.4	---	---	1.7	1.2	1.2
24		1.17	341	259	7.84	49.2	32.8	7.4	---	---	1.7	1.2	1.3
25	Diffusion	1.16	346	260	7.71	49.5	32.5	7.4	---	---	1.7	1.2	1.3
26	bonded (T)	1.19	345	260	7.94	49.5	32.5	7.4	---	---	1.7	1.2	1.3
27		1.13	345	260	7.47	49.5	32.5	7.4	---	---	1.6	1.2	1.2

[a]Cross-sectional area of stiffened panel.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY

SKIN-STRINGER PANELS – Concluded

(c) Panels fabricated from triplex-annealed sheet

U.S. Customary Units													
Test	Panel type	Mass, lbm	Length, in.	Width, in.	Area,[a] in^2	b_S, in.	b_W, in.	b_F, in.	b_A, in.	b_O, in.	t_S, in.	t_W, in.	t_F, in.
1	Tungsten inert-gas welded	1.206	9.47	7.50	0.806	1.33	1.33	0.54	---	---	0.044	0.044	0.044
2		1.189	9.44	7.48	.797	1.34	1.34	.55	---	---	.045	.043	.043
3		1.115	9.25	6.81	.763	1.34	1.34	.54	---	---	.044	.042	.042
4		1.245	9.82	7.50	.804	1.35	1.34	.55	---	---	.046	.043	.043
5	Riveted	1.390	9.50	7.18	0.926	1.35	1.34	0.54	0.43	0.26	0.046	0.046	0.046
6		1.383	9.50	7.20	.922	1.35	1.34	.54	.43	.25	.045	.045	.045
7		1.390	9.48	7.29	.928	1.35	1.35	.54	.43	.26	.045	.045	.045
8	Resistance-spotwelded	1.448	9.48	7.33	0.967	1.35	1.35	0.53	0.54	0.32	0.047	0.045	0.045
9		1.476	9.46	7.33	.988	1.35	1.35	.53	.55	.34	.067	.047	.047
10		1.471	9.42	7.34	.988	1.34	1.35	.54	.54	.32	.046	.047	.047

SI Units													
Test	Panel type	Mass, kg	Length, mm	Width, mm	Area,[a] cm^2	b_S, mm	b_W, mm	b_F, mm	b_A, mm	b_O, mm	t_S, mm	t_W, mm	t_F, mm
1	Tungsten inert-gas welded	0.547	241	191	5.20	33.8	33.8	13.7	---	---	1.1	1.1	1.1
2		.540	240	190	5.14	34.0	34.0	14.0	---	---	1.1	1.1	1.1
3		.506	235	173	4.92	34.0	33.8	13.7	---	---	1.1	1.1	1.1
4		.565	249	191	5.19	34.3	34.0	14.0	---	---	1.2	1.1	1.1
5	Riveted	0.630	241	182	5.97	34.3	34.0	13.7	10.9	6.6	1.2	1.2	1.2
6		.627	241	183	5.95	34.3	34.3	13.7	10.9	6.4	1.1	1.1	1.1
7		.630	241	185	5.99	34.3	34.3	13.7	10.9	6.6	1.1	1.1	1.1
8	Resistance-spotwelded	0.657	241	186	6.24	34.3	34.3	13.5	13.7	8.1	1.2	1.1	1.1
9		.669	240	186	6.37	34.3	34.3	13.5	14.0	8.6	1.2	1.2	1.2
10		.667	239	186	6.37	34.0	34.3	13.7	13.7	8.1	1.2	1.2	1.2

[a]Cross-sectional area of stiffened panel.

TABLE III.- MATERIAL PROPERTIES OF Ti-8Al-1Mo-1V TITANIUM-ALLOY

IN THREE HEAT TREATED CONDITIONS[a]

(a) Mill-annealed (plate)

Specimen axis relative to rolling direction	Yield stress				Tensile strength		Young's modulus			
	Tensile		Compressive				Tensile		Compressive	
	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	GN/m^2
Longitudinal	120.0	830	134.0	920	127.8	880	17 350	120	17 790	123
Transverse	119.7	830	138.7	960	127.3	880	-----	---	-----	---
Thickness	123.2	850	146.3	1000	135.0	930	-----	---	-----	---

[a]Data are averages of four tests.

(b) Duplex-annealed (sheet)

Panel type	Component	Sheet thickness		Yield stress				Tensile strength		Young's modulus				Elongation, percent	
				Tensile		Compressive				Tensile		Compressive			
		in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	GN/m^2	2 in. (5 cm)	Uniform
Tungsten inert-gas welded	Stringer	0.050	1.27	134.8	930	146.5	1010	147.9	1020	18 090.0	125	18 780.0	129	14.0	9.0
	Skin	.064	1.63	----	---	----	----	----	----	-------	---	-------	---	---	---
Riveted[a]	Stringer	0.050	1.27	136.2	940	142.4	980	147.9	1020	17 200.0	119	-------	---	14.5	9.5
	Skin	.064	1.63	137.8	950	151.9	1050	150.5	1040	18 100.0	125	-------	---	14.0	8.0
Resistance-spotwelded	Stringer	0.050	1.27	130.0	900	133.0	920	146.0	1010	-------	---	-------	---	14.5	10.5
	Skin	.064	1.63	134.0	920	140.0	970	146.0	1010	-------	---	17 790.0	123	15.0	11.0
Arc-spotwelded[a]	Stringer	0.050	1.27	136.2	940	142.4	980	147.9	1020	17 200.0	119	-------	---	14.5	9.5
	Skin	.064	1.63	137.8	950	151.9	1050	150.5	1040	18 100.0	125	-------	---	14.0	8.0
Electron-beam welded	Stringer	0.050	1.27	133.0	920	139.2	960	148.0	1020	17 000.0	117	-------	---	14.0	9.5
	Skin	.064	1.63	138.4	950	150.0	1030	151.0	1040	18 200.0	125	-------	---	13.0	8.5
Diffusion bonded (Z)	Stringer	0.050	1.27	128.3	880	137.2	950	139.0	960	18 040.0	125	18 460.0	127	20.5	14.0
	Skin	.064	1.63	132.1	910	144.6	1000	142.8	980	18 500.0	128	19 000.0	131	18.0	15.0
Diffusion bonded (T)	Cap	0.050	1.27	138.0	950	160.0	1100	139.8	960	20 000.0	138	20 300.0	140	2.5	2.0
	Web	.050	1.27	127.4	880	138.2	950	139.0	960	18 500.0	128	19 050.0	131	17.0	10.0
	Skin	.064	1.63	134.0	920	144.0	990	145.0	1000	18 600.0	128	19 900.0	137	15.0	10.0

[a]Riveted and arc-spotwelded panels were fabricated from same sheets.

(c) Triplex-annealed (sheet)

Panel type (a)	Sheet thickness		Yield stress				Tensile strength		Young's modulus				Elongation, percent	
			Tensile		Compressive				Tensile		Compressive			
	in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	GN/m^2	2 in. (5 cm)	Uniform
Tungsten inert-gas welded	0.050	1.27	134.0	920	145.1	1000	148.5	1020	18 350.0	127	-------	---	15.0	10.0
	.050	1.27	----	---	[b]146.0	[b]1010	----	----	-------	---	-------	---	---	---
Riveted and resistance-spotwelded[c]	0.050	1.27	139.0	960	148.1	1020	153.0	1050	18 800.0	130	18 660.0	129	12.0	8.0

[a]Stringers and skin were fabricated from same sheet for each panel type.
[b]Specimen was stress relieved 30 minutes at 1450° F (1060° K) in argon.
[c]Riveted and resistance-spotwelded panels were fabricated from same sheet.

TABLE IV.- TEST RESULTS FOR Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS

(a) Integral panels machined from mill-annealed plate

Test	P_{max}		σ_{max}		σ_{cr} (strain reversal)		σ_{cr} (shortening deviation)	
	kips	MN	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2
1	149	0.66	81.4	561	---	---	---	---
2	171	.76	84.2	561	59.7	412	59.1	407

TABLE IV.- TEST RESULTS FOR Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Continued

(b) Panels fabricated from duplex-annealed sheet

Test	Panel type	P_{max}		σ_{max}		σ_{cr} (strain reversal)		σ_{cr} (shortening deviation)	
		kips	MN	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2
[a]1	Tungsten inert-gas welded	116.6	0.518	94.6	652	73.4	506	74.2	512
2		102.8	.457	83.2	574	53.2	367	55.8	385
3		103.0	.458	83.1	573	52.9	365	54.8	378
4	Riveted	105.0	0.467	78.5	541	71.1	490	72.4	499
5		113.7	.506	83.2	574	69.8	481	75.4	520
6		107.4	.478	80.0	552	71.0	490	74.4	513
7	Resistance-spotwelded	119.6	0.532	85.8	592	79.9	551	83.2	574
8		123.2	.548	88.3	608	76.4	527	76.3	526
9		118.8	.528	84.9	585	76.4	527	---	---
10	Arc-spotwelded	99.3	0.442	71.4	492	56.5	390	61.7	425
11		100.4	.447	69.8	481	59.4	410	61.2	422
12		102.4	.455	73.5	507	57.8	399	69.7	481
13	Electron-beam welded (Z)	95.4	0.424	85.4	589	62.7	432	71.7	494
14		97.4	.433	86.4	596	71.5	493	71.9	496
15		96.0	.427	85.2	587	72.6	501	72.0	496
16	Electron-beam welded (L)	83.5	0.371	82.8	571	66.1	456	65.5	452
17		84.4	.375	83.0	572	64.5	445	64.0	441
18		83.8	.373	82.6	570	64.3	443	65.0	448
19	Diffusion bonded (Z)	124.4	0.553	92.9	641	80.1	552	87.3	602
20		129.5	.576	97.0	669	84.3	581	86.9	599
21		106.5	.474	96.8	667	84.4	581	89.1	614
22		125.0	.556	93.4	644	84.7	584	90.3	623
23	Diffusion bonded (T)	120.0	0.534	98.8	681	70.7	487	75.7	522
24		118.0	.525	97.2	670	71.5	493	78.2	539
[b]25		77.5	.345	64.7	446	64.1	442	---	---
26		115.2	.512	94.0	648	60.5	417	71.6	494
[b]27		95.3	.424	82.5	569	63.5	438	---	---

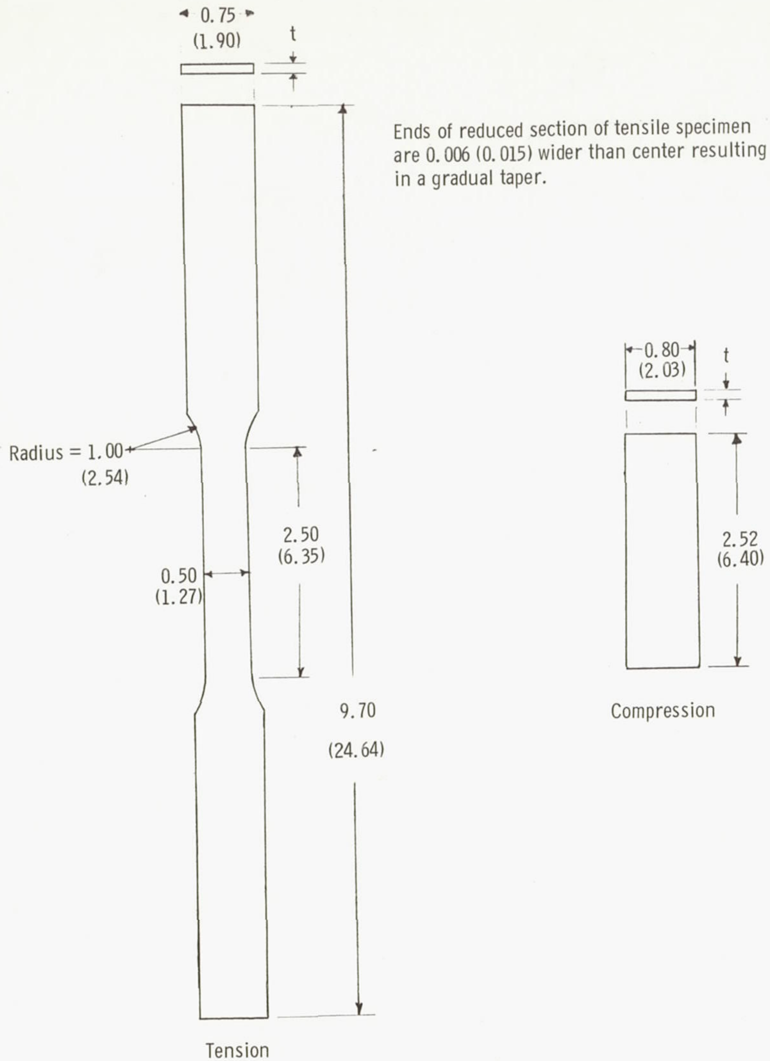
[a]Stress relieved 30 minutes at 1450° F (1060° K) in argon before testing.
[b]Premature failure due to defective bonding.

TABLE IV.- TEST RESULTS FOR Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Concluded

(c) Panels fabricated from triplex-annealed sheet

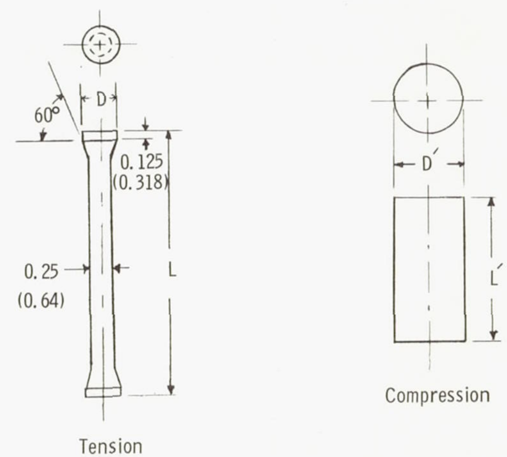
Test	Panel type	P_{max}		σ_{max}		σ_{cr} (strain reversal)		σ_{cr} (shortening deviation)	
		kips	MN	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2
1	Tungsten inert-gas welded	60.3	0.268	74.8	516	49.8	343	53.4	368
2		60.0	.267	75.3	519	52.1	359	55.2	381
3		55.3	.246	72.5	500	50.1	345	49.8	343
[a]4		67.8	.302	84.3	581	---	---	---	---
5	Riveted	70.4	0.313	76.0	524	68.1	470	68.0	469
6		71.0	.316	77.0	531	65.1	449	70.0	483
7		70.1	.312	75.5	521	---	---	66.8	461
8	Resistance-spotwelded	80.2	0.357	82.9	572	71.0	490	74.5	514
9		83.0	.369	84.0	580	75.8	523	77.8	536
10		86.5	.385	87.6	604	80.6	556	81.0	558

[a]Stress relieved 30 minutes at 1450° F (1060° K) in argon before testing.



(a) Specimens from sheet material.

Orientation of specimen axis relative to plate rolling direction			
	Longitudinal	Transverse	Thickness
L	3.00 (7.62)	3.00 (7.62)	1.75 (4.45)
D	0.375 (0.95)	0.375 (0.95)	0.375 (0.95)
L′	2.50 (6.35)	2.50 (6.35)	1.70 (4.32)
D′	0.800 (2.03)	0.800 (2.03)	0.600 (1.52)



(b) Specimens from plate material.

Figure 1.- Specimens for determination of mechanical properties of materials. Dimensions are in inches (centimeters).

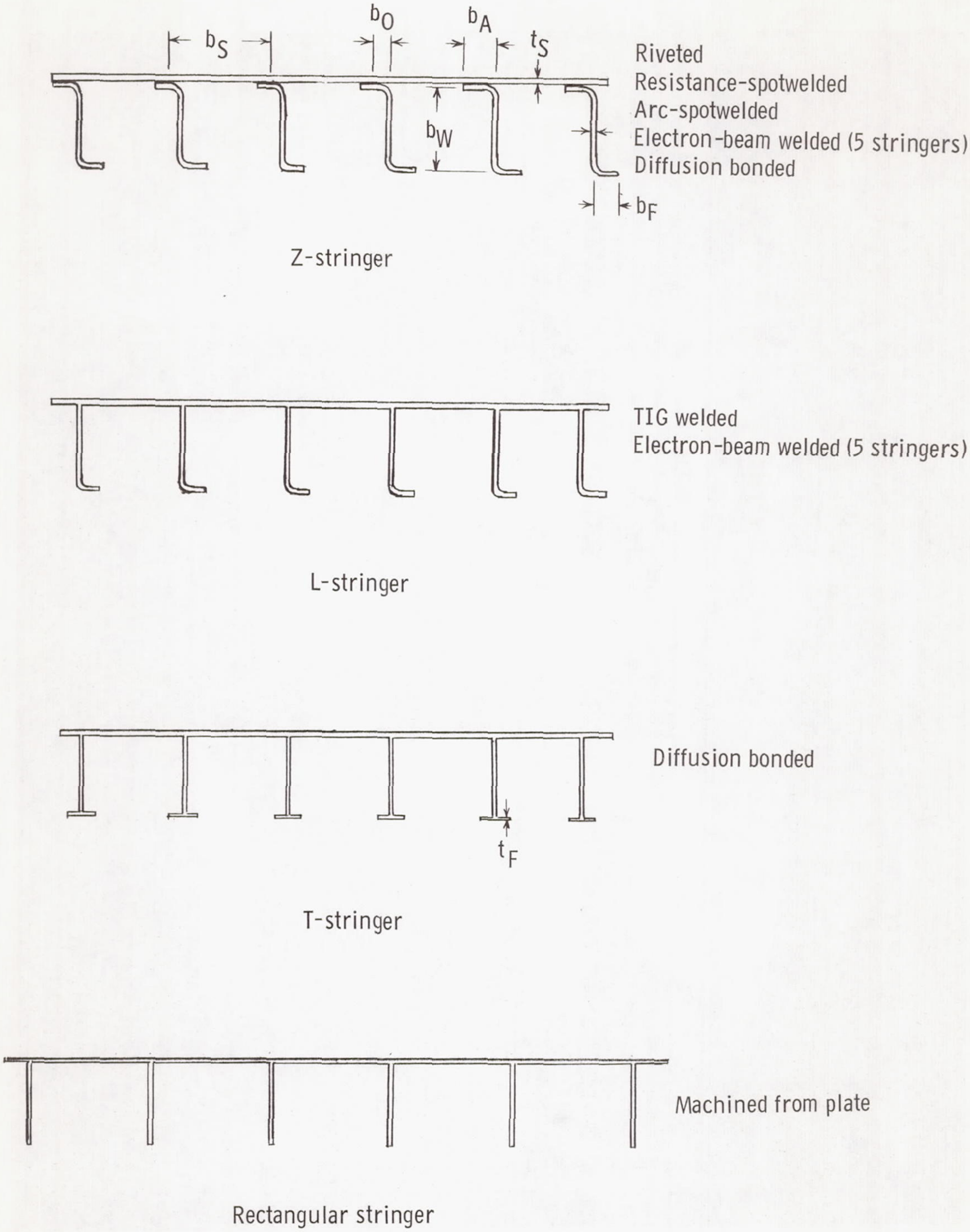


Figure 2.- Cross section of skin-stringer panels.

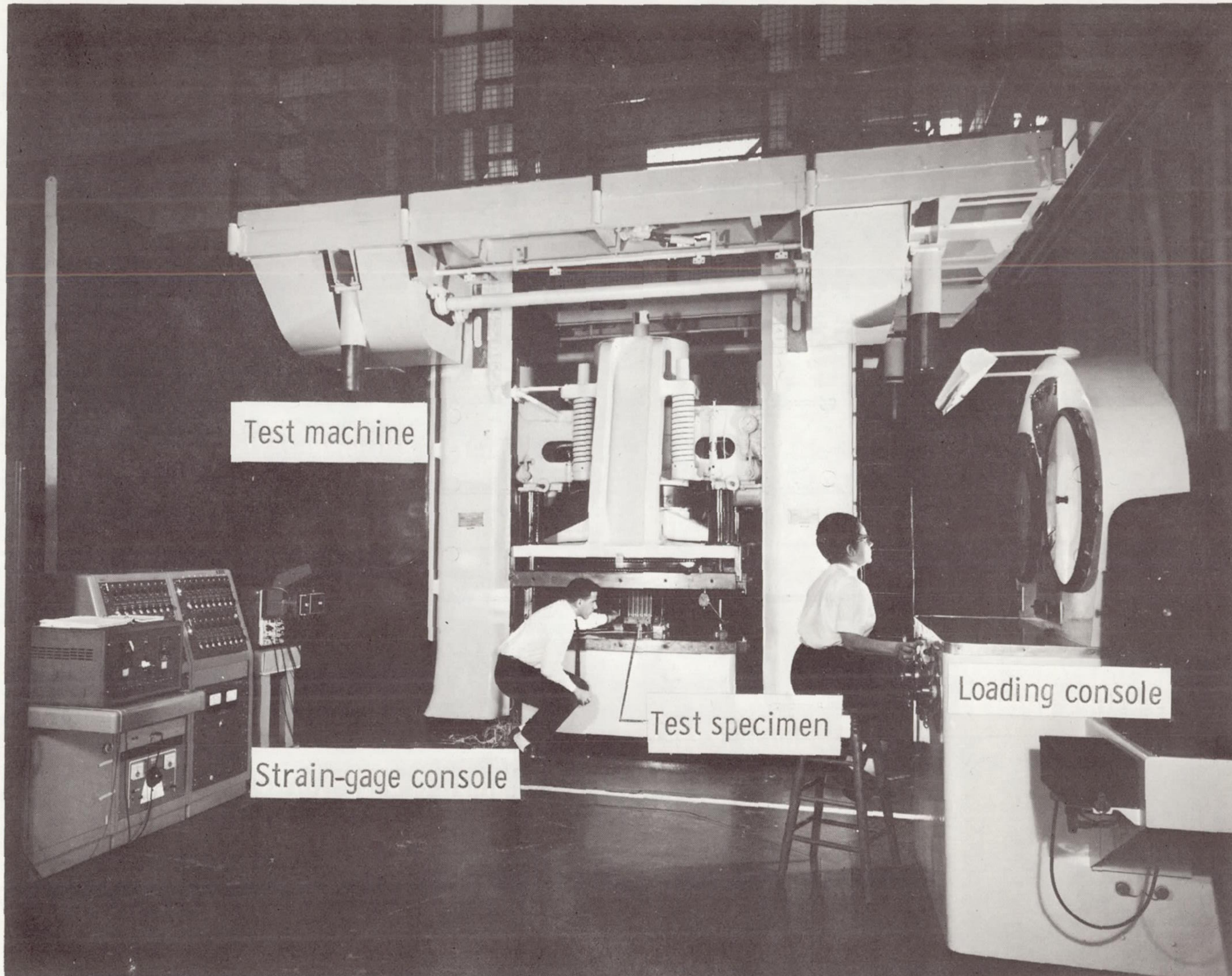
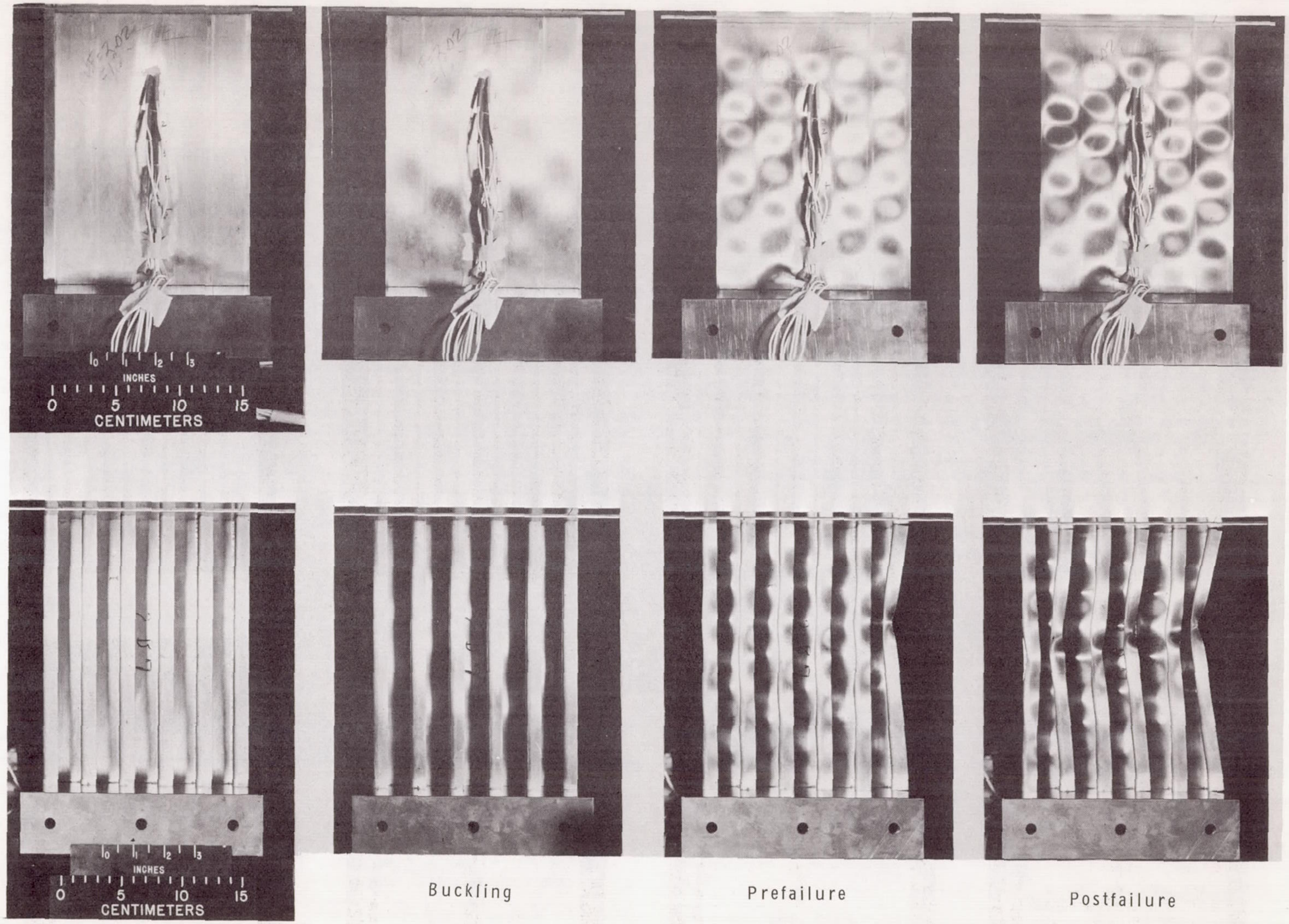


Figure 3.- Test setup for skin-stringer panels.

L-64-5402

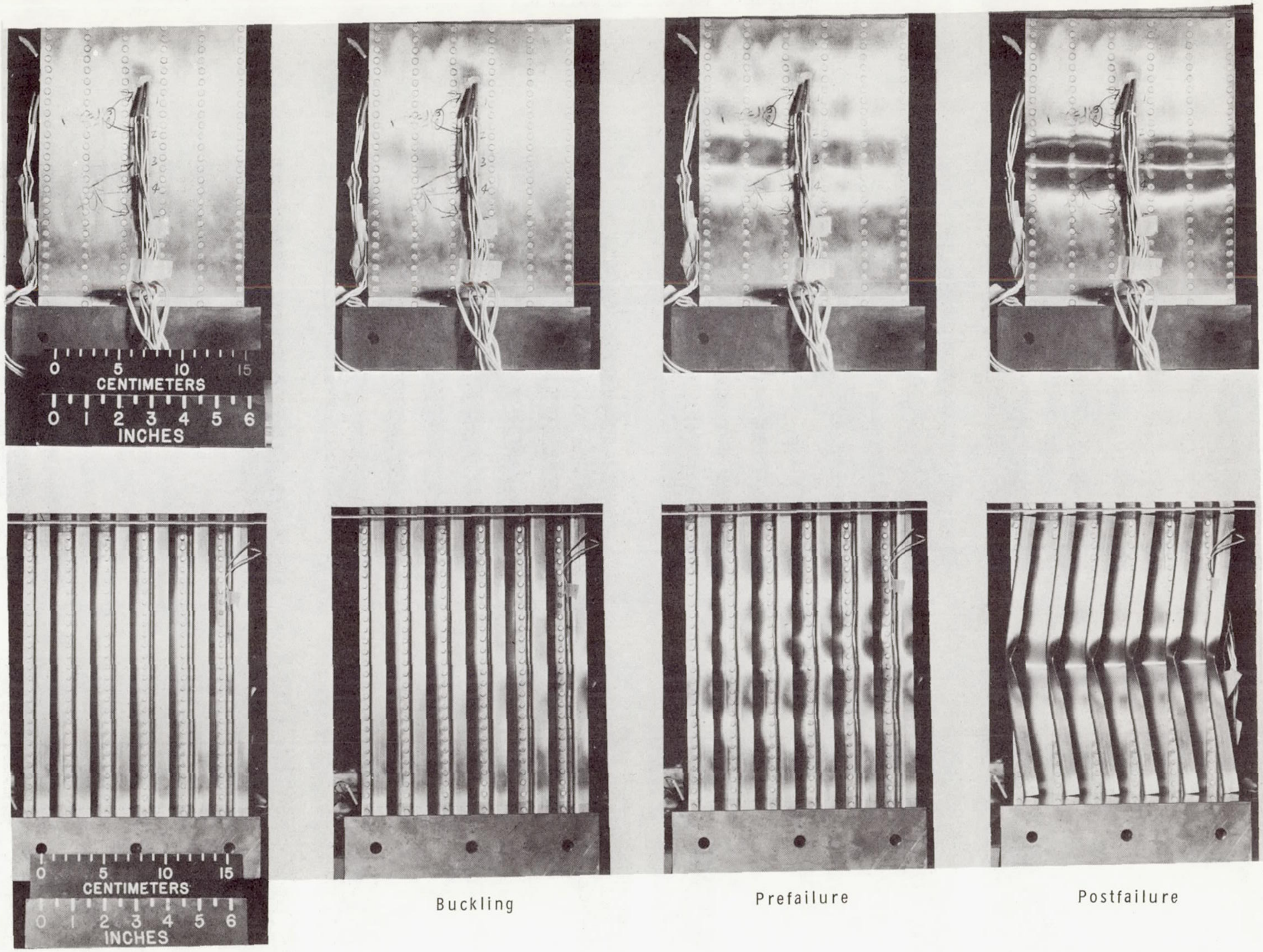


Start Buckling Prefailure Postfailure

(a) Tungsten inert-gas welded (triplex-annealed material).

L-69-5230

Figure 4.- Photographs of panels and modes of failure.



Start

Buckling

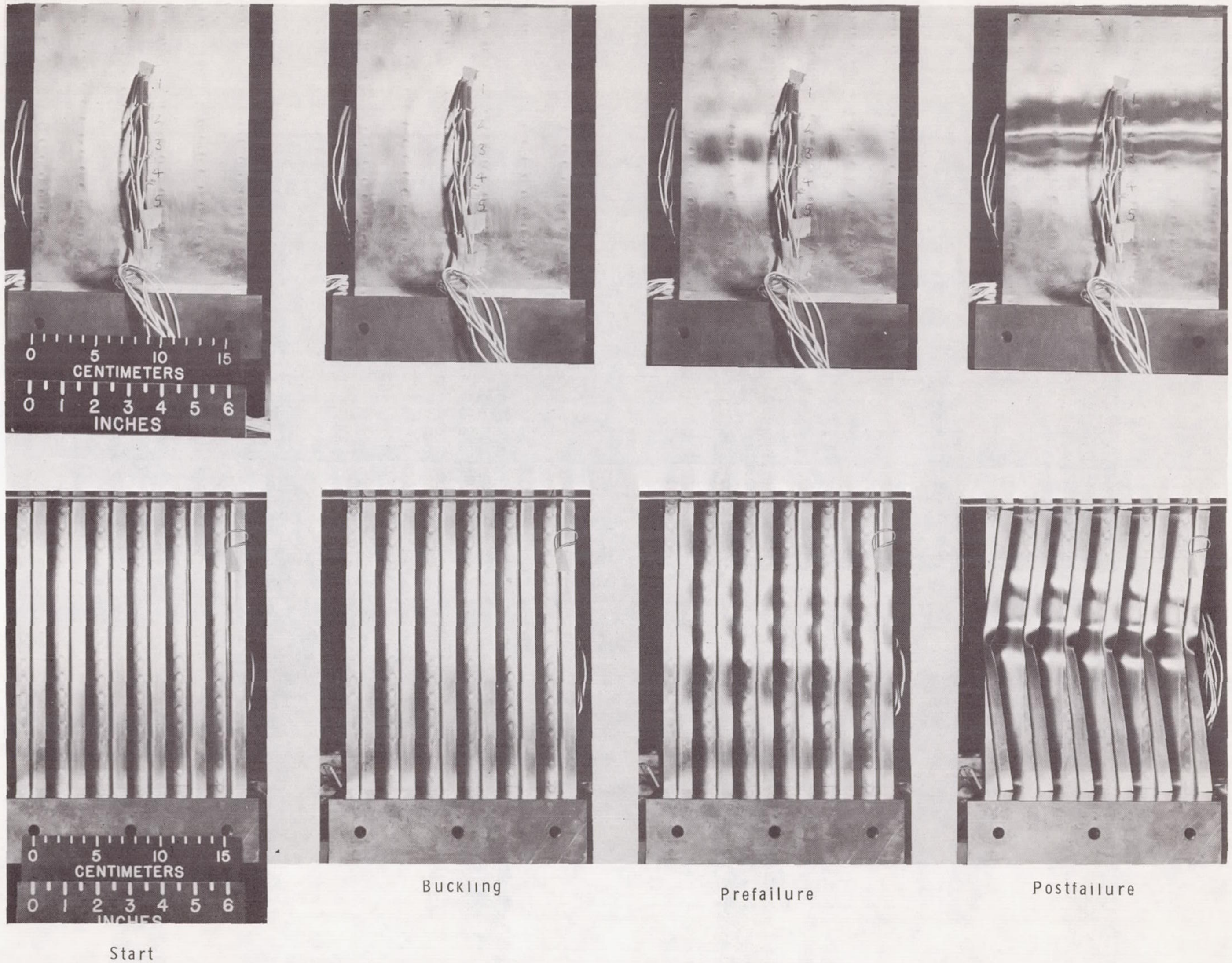
Prefailure

Postfailure

(b) Riveted (triplex-annealed material).

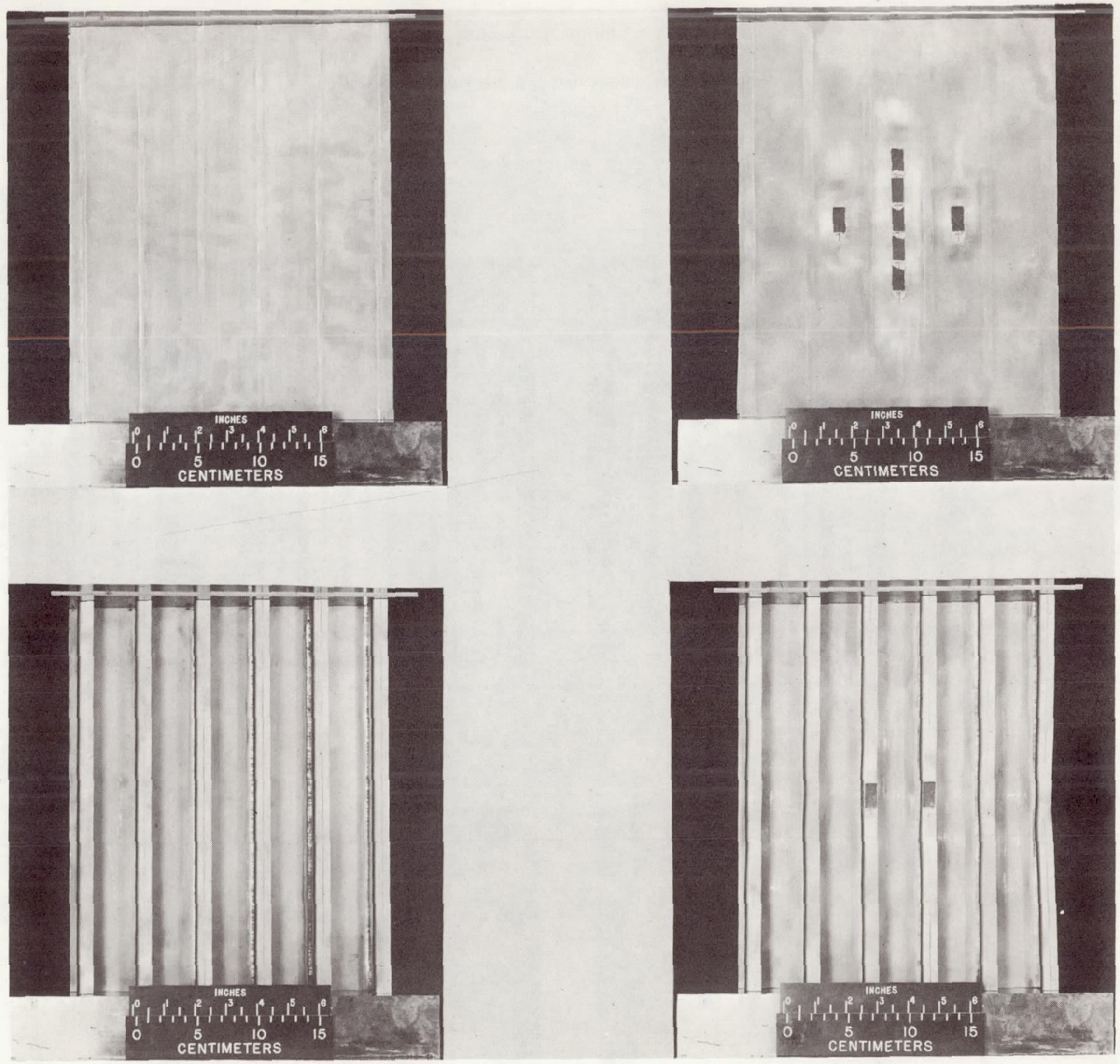
L-69-5231

Figure 4.- Continued.



(c) Resistance-spotwelded (triplex-annealed material). L-69-5232

Figure 4.- Continued.

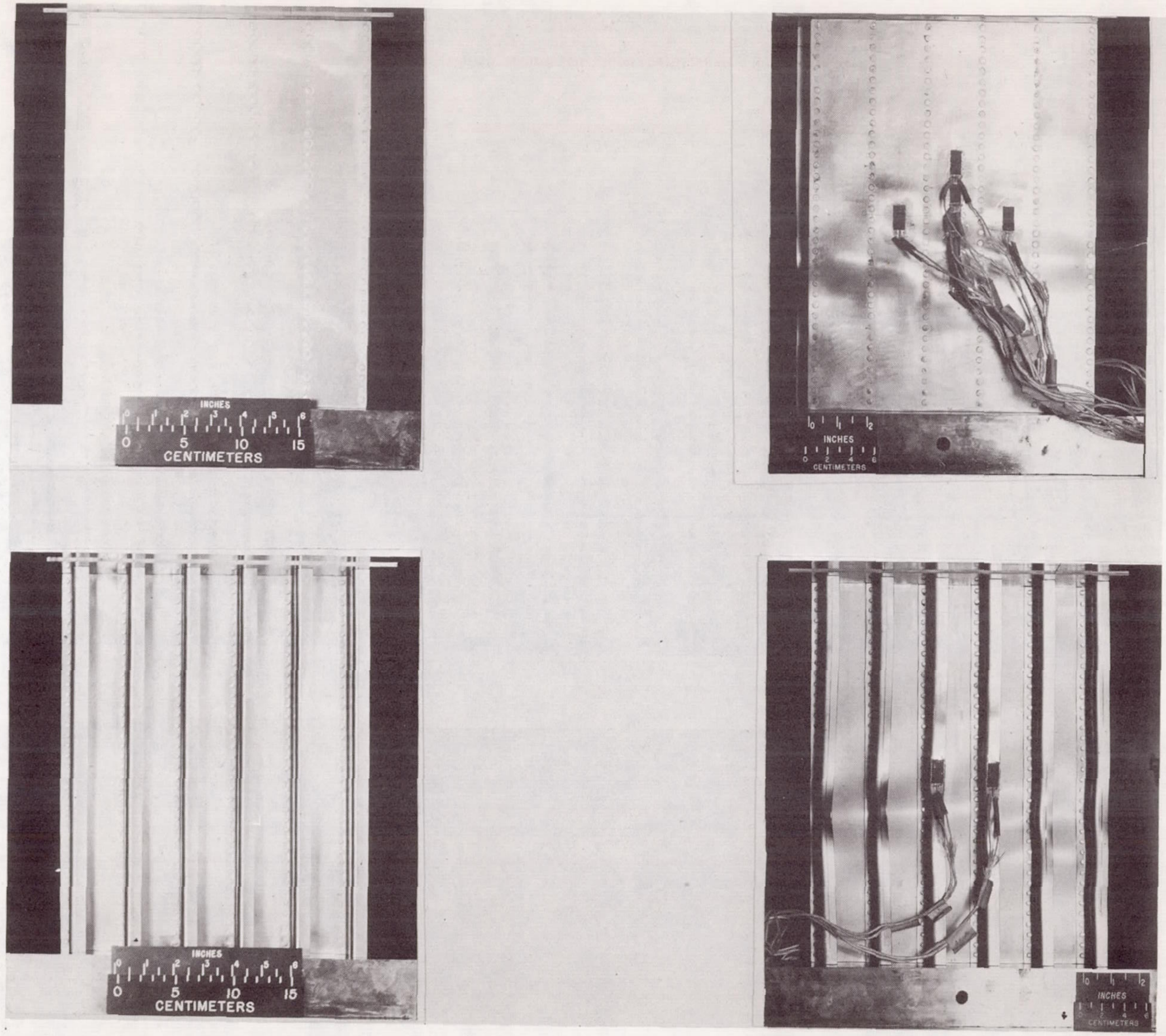


Start

Postfailure

(d) Tungsten inert-gas welded (duplex-annealed material). L-69-5233

Figure 4.- Continued.

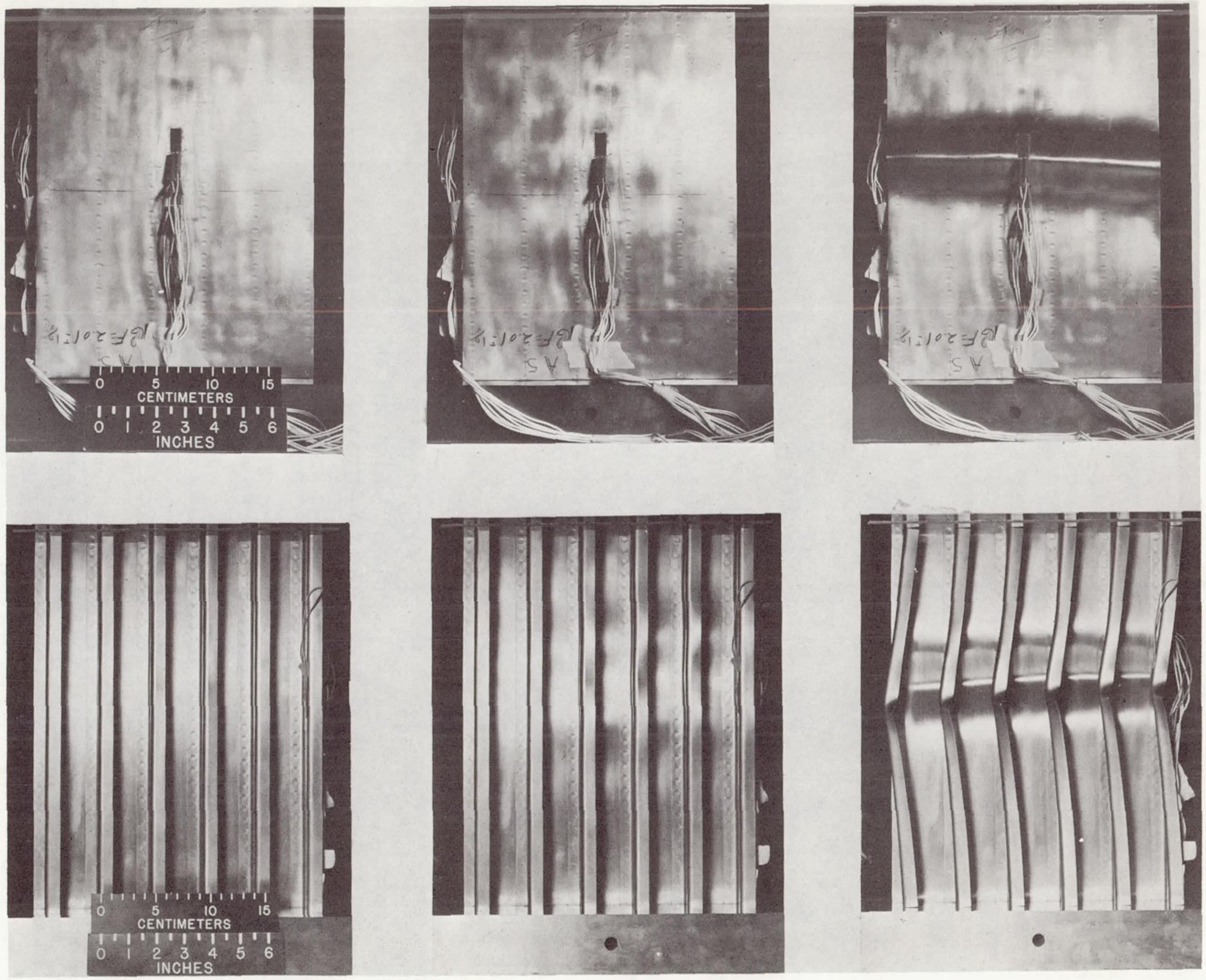


Start

Postfailure

(e) Riveted (duplex-annealed material). L-69-5234

Figure 4.- Continued.

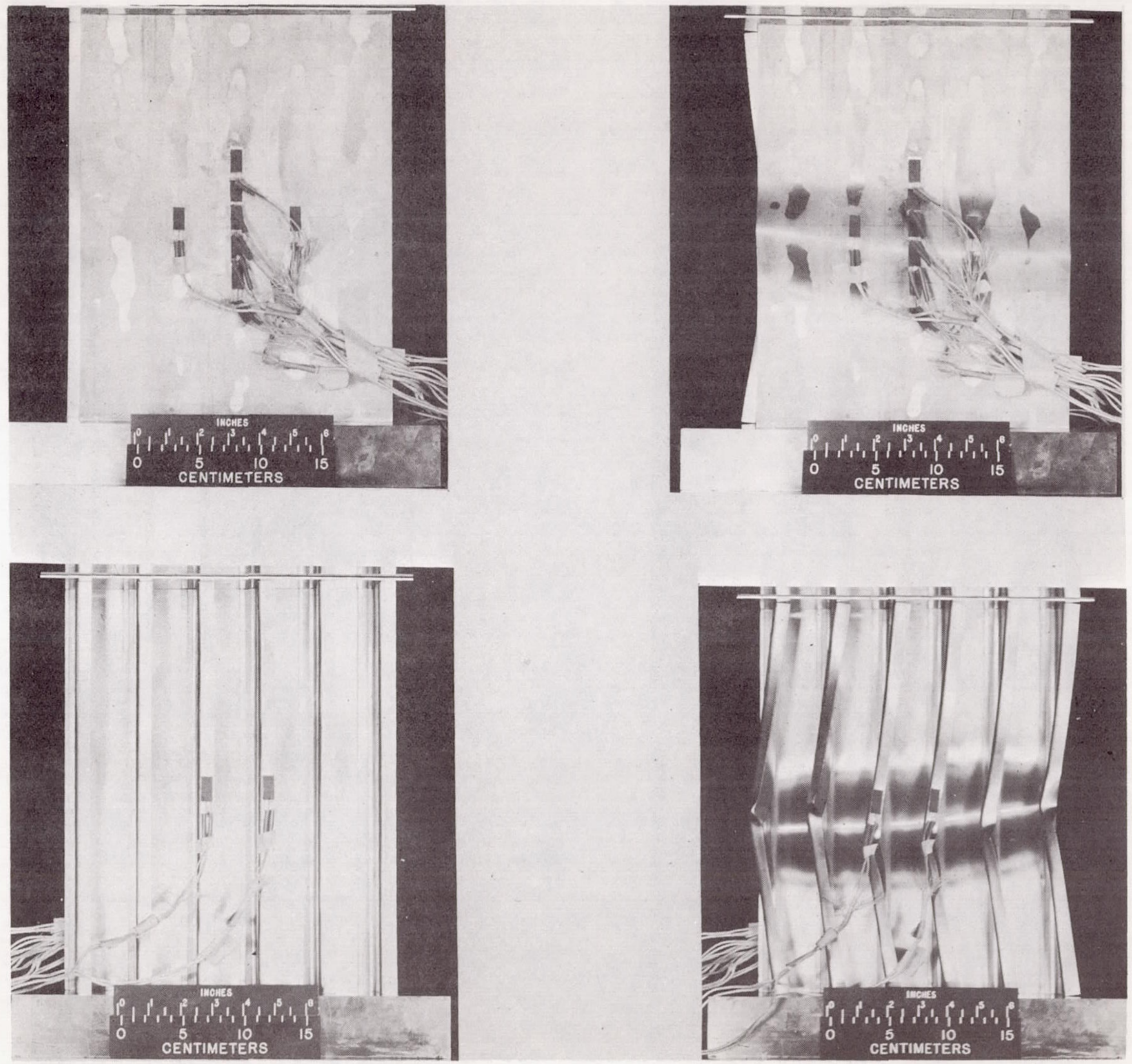


Start Buckling Postfailure

(f) Resistance-spotwelded (duplex-annealed material).

L-69-5235

Figure 4.- Continued.

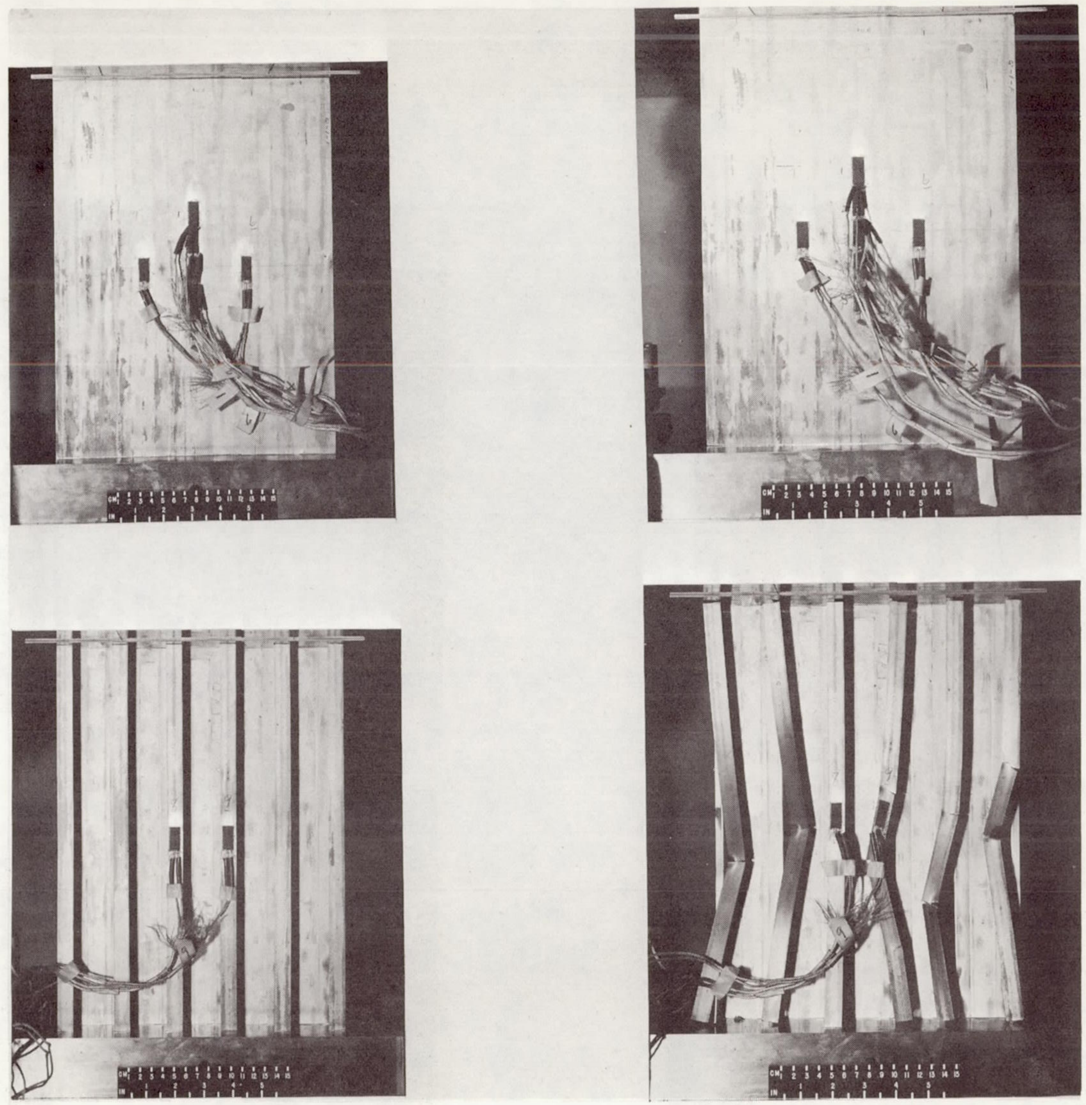


Start

Postfailure

(g) Diffusion bonded (duplex-annealed material) Z-stringers. L-69-5236

Figure 4.- Continued.



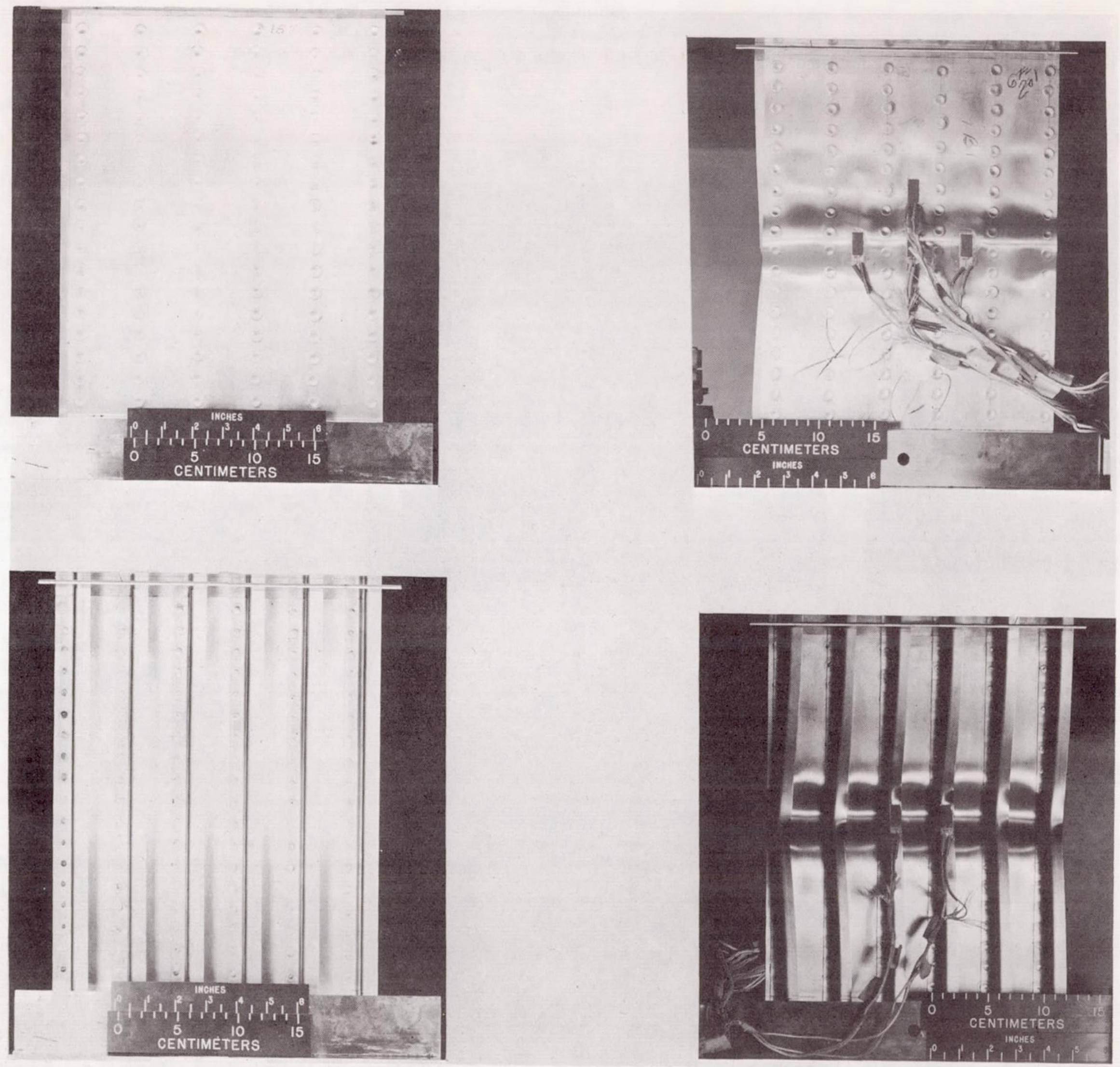
Start

Postfailure

(h) Diffusion bonded (duplex-annealed material) T-stringers.

L-69-5237

Figure 4.- Continued.

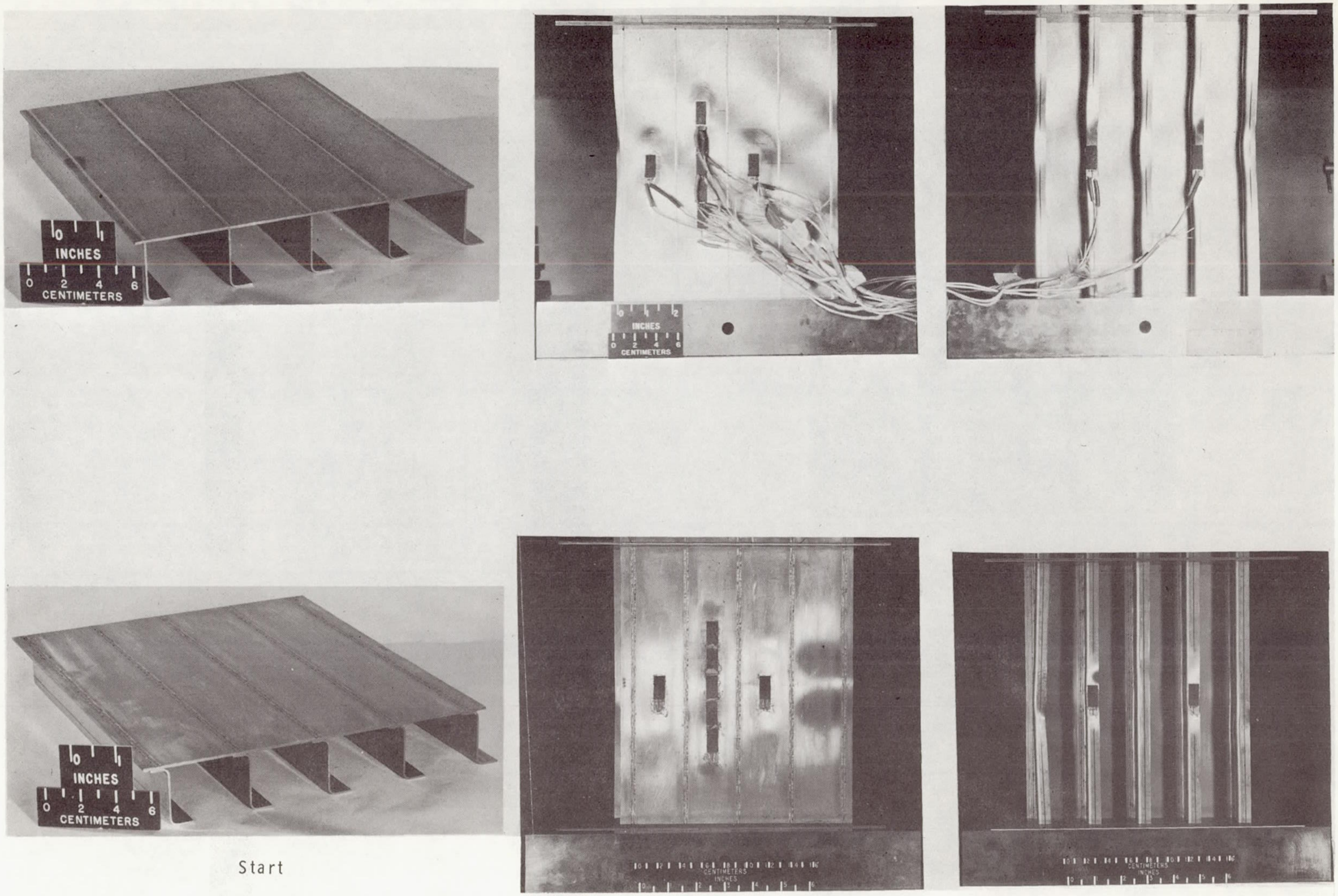


Start

Postfailure

(i) Arc-spotwelded (duplex-annealed material). L-69-5238

Figure 4.- Continued.



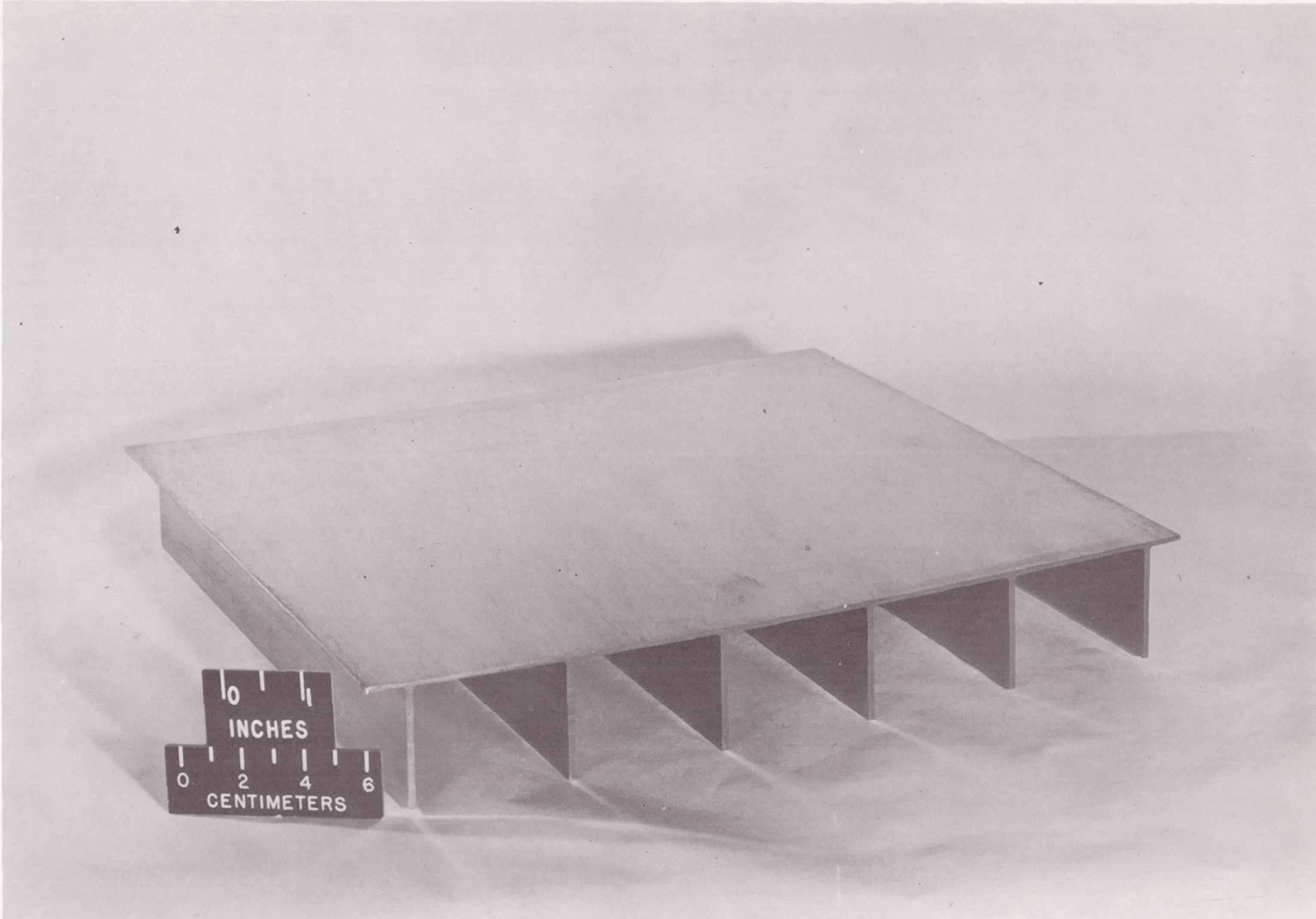
Start

Postfailure

(j) Electron-beam welded (duplex-annealed material) L- and Z-stringers.

L-69-5239

Figure 4.- Continued.



(k) Machined from plate (mill-annealed material).

L-64-9145

Figure 4.- Concluded.

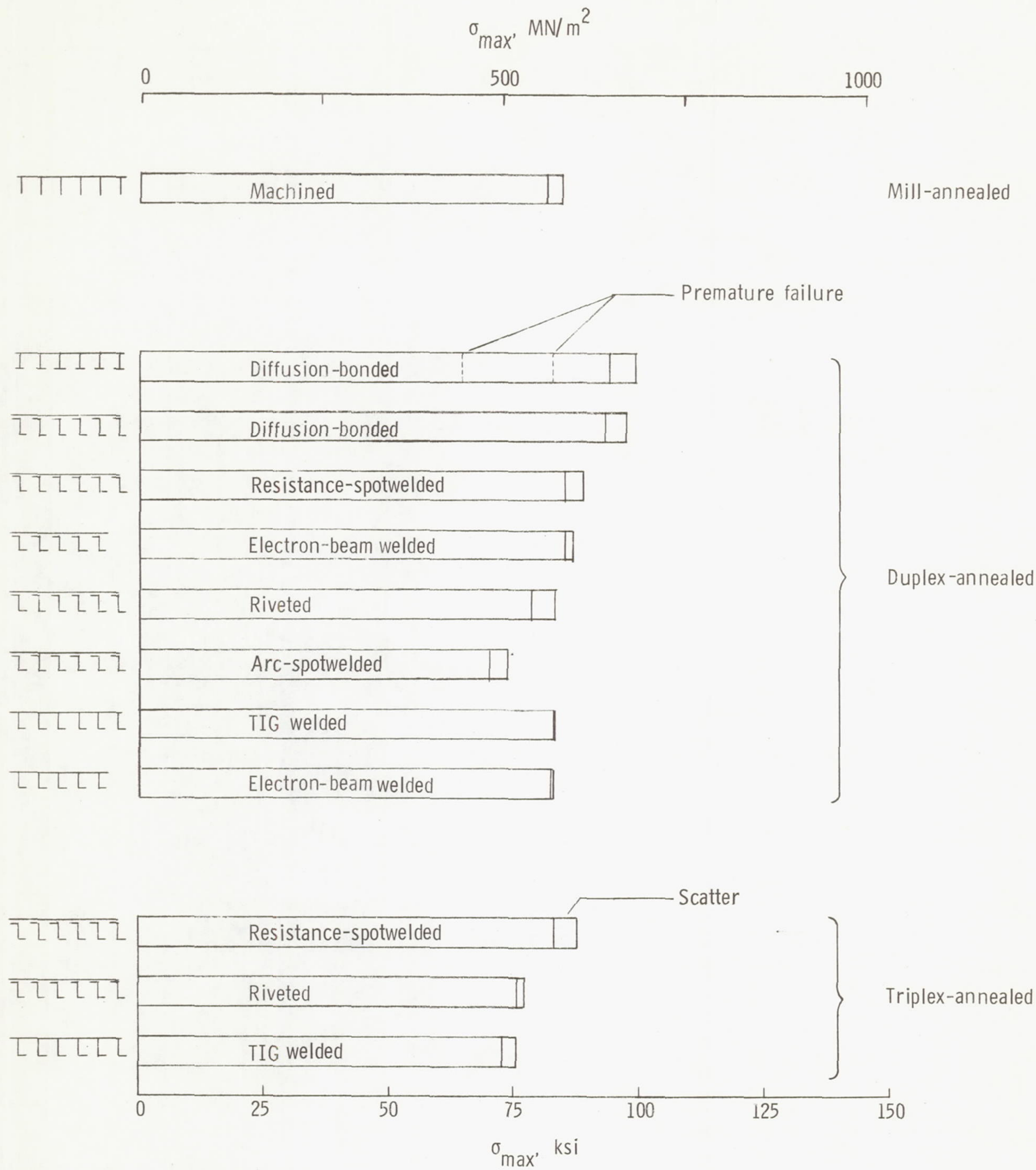


Figure 5.- Maximum compressive strengths of Ti-8Al-1Mo-1V titanium-alloy skin-stringer panels.

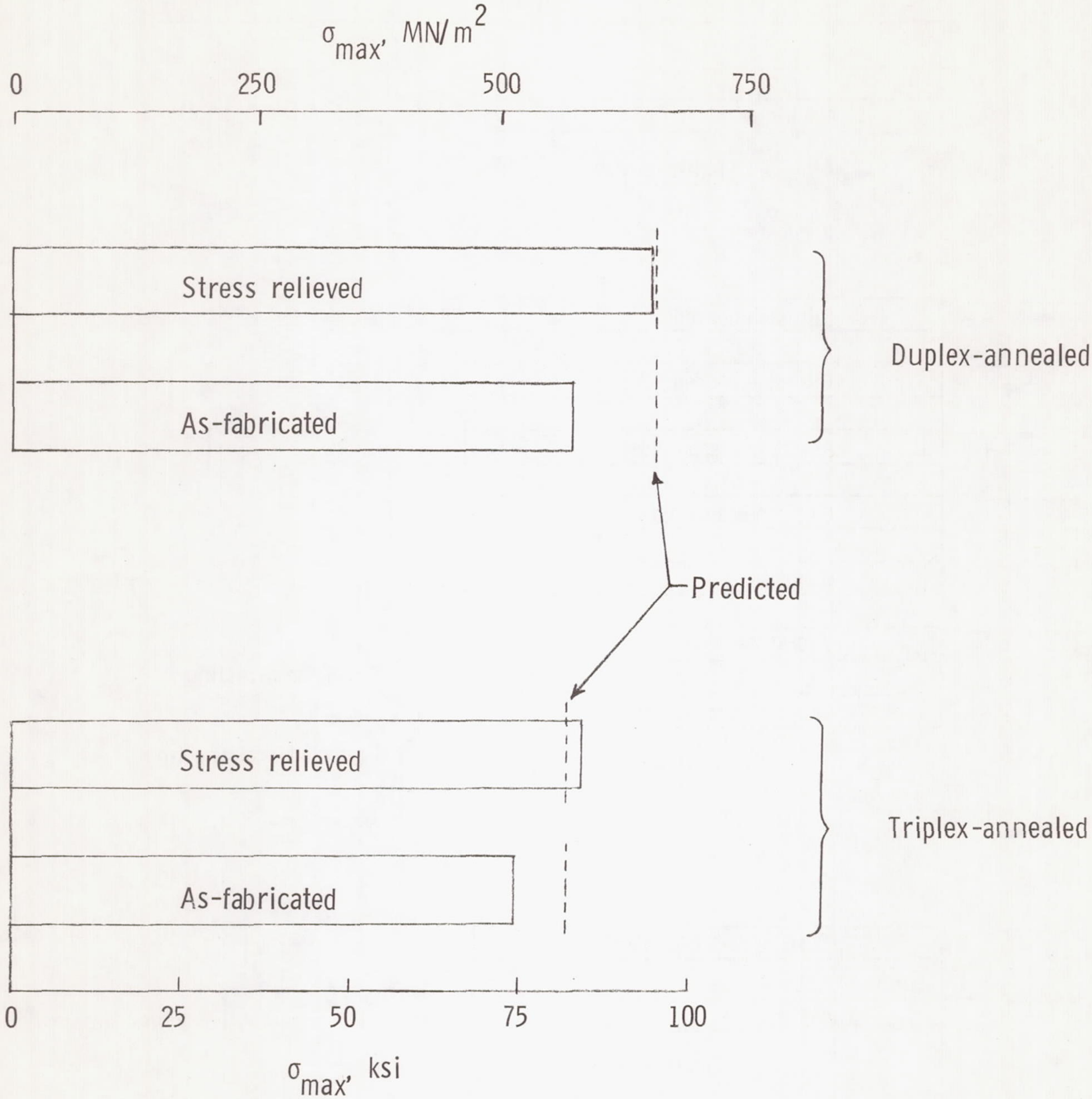


Figure 6.- Comparison of maximum compressive strengths before and after stress relief for TIG welded panels with L-stringers.

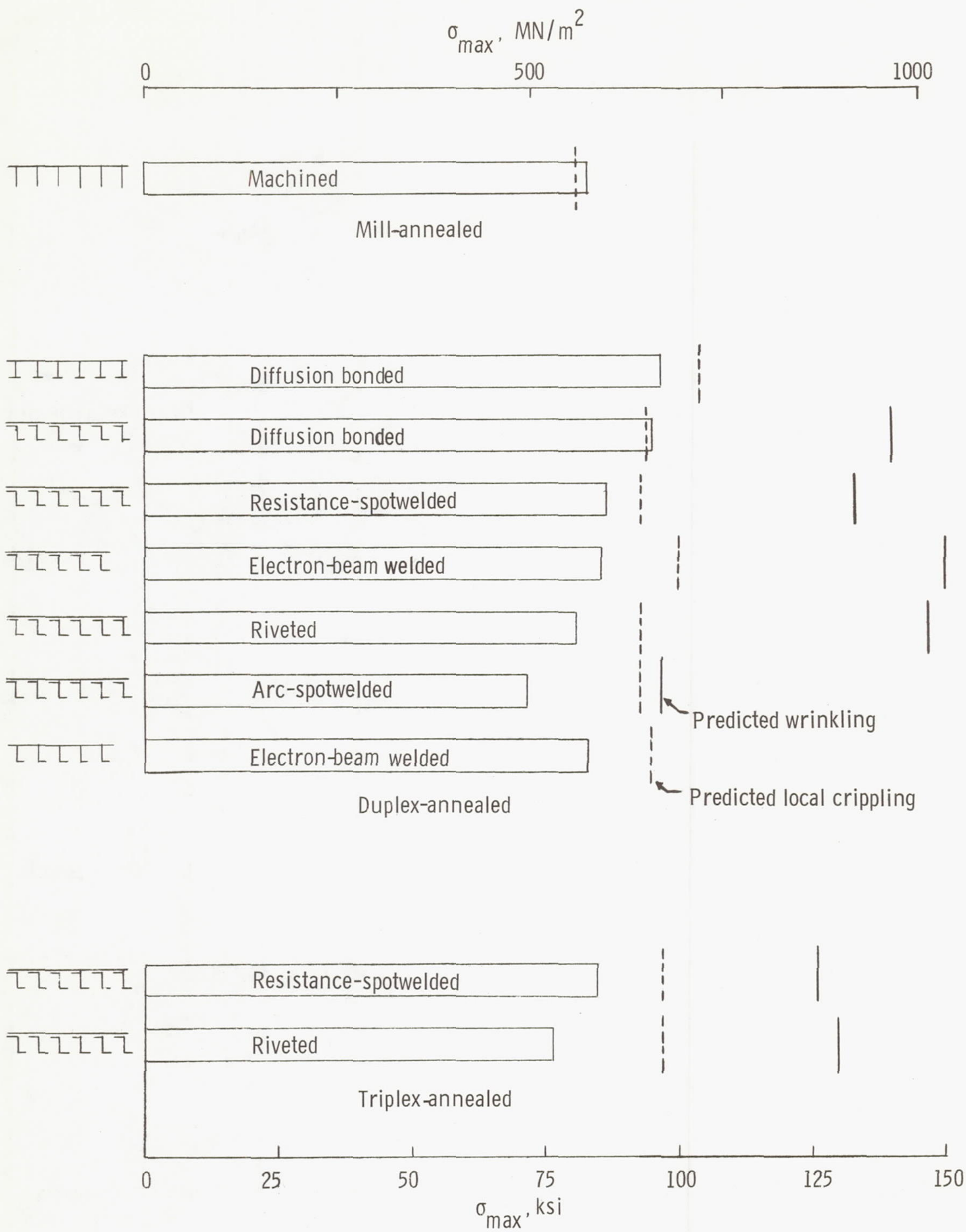


Figure 7.- Comparison of experimental and predicted maximum compressive strengths for Ti-8Al-1Mo-1V titanium-alloy skin-stringer panels.

NASA-Langley, 1969 —— 15 L-6645